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ANALYSIS OF THE EFFECTS OF BOUNDARY-LAYER CONTROL

ON THE TAKE-OFF PERFORMANCE CHARACTERISTICS

OF A LIAISON-TYPE AIRPLANE

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SUMMARY

A performance analysis has been made to determine whether boundary-layer control by suction might reduce the minimum take-off distance of a four-place or five-place liaison-type airplane below that obtainable with conventional high-lift devices. The airplane was assumed to be capable of operating from airstrips having a ground friction coefficient of 0.2. The pay load was fixed at 1500 pounds and the wing span was varied from 30 to 100 feet, the aspect ratio from 5 to 15, and the power from 200 to 1300 horsepower. Maximum lift coefficients of 5.0 and 2.8 were assumed for the airplanes with and without boundary-layer control, respectively. A conservative estimate of the boundary-layer-control-equipment weight was included. The effects of the boundary-layer control on total take-off distance, ground run, and stalling speed were determined

The analysis indicates that the addition of boundary-layer control does not reduce the absolute minimum total take-off distance that is obtained with an airplane having a low wing loading and a moderately low aspect ratio. The effectiveness of boundary-layer control in reducing the total take-off distance for a given maximum speed improves with increasing aspect ratio and, for wing loadings of 10 pounds per square foot or more and an aspect ratio of 10 or more, the addition of boundary-layer control results in a decrease in the total take-off distance.

For a given maximum speed the ground run was reduced for all configurations by the addition of boundary-layer control. The reduction was negligible for aspect ratio of 5 but was 10 to 30 percent for aspect ratios of 10 and 15. The stalling speed for a given maximum speed was reduced 20 to 25 percent for all configurations by application of boundary-layer control. A reduction in the weight of the boundary-layer-control equipment would result in an appreciable decrease in the total take-off and ground run distances, but would have a negligible effect on the stalling speed. The optimum power loading for minimum total take-off distance, regardless of wing loading or aspect ratio, was found to be approximately 8.5 and 9.0 pounds per brake horsepower for the conventional and boundary-layer-control airplanes, respectively.

INTRODUCTION

Investigations have been conducted in both wind tunnels and flight to increase the maximum lift coefficient of airfoils by use of boundary-layer control. By this means, an airplane lift coefficient of 4.2 was obtained in the flight investigation of reference 1, and the wind-tunnel tests of reference 2 have indicated that section lift coefficients of 5.5 may be obtained by proper application of boundary-layer control. In contrast, conventional leading- or trailing-edge high-lift devices have not been capable of producing airplane maximum lift coefficients much in excess of 2.8 (reference 3). There is, however, some question as to the exact benefits to be obtained by use of the high lift coefficients available with boundary-layer control. For example, increasing the gross weight of an airplane by the addition of the boundary-layer-control equipment will tend to offset the benefit from increasing the lift coefficient. In addition, the increase in induced drag with increased lift coefficients may reduce the angle of climb in take-off or increase the sinking speed during the landing maneuver to the point where increasing the lift coefficient may be detrimental to the landing or take-off performance. Accordingly, a performance analysis was undertaken to determine whether boundary-layer control by suction could be incorporated in an airplane design to reduce the minimum take-off distance required to clear an obstacle below that obtainable with conventional high-lift devices.

The analysis was made for a 4-place or 5-place or liaison-type airplane having a 1500-pound pay load since an airplane of this type might be expected to operate from small makeshift airports where take-off distance would be of primary importance. The power, aspect ratio, and span were varied over a range sufficiently large to insure obtaining the optimum airplane configuration for minimum take-off distance. The effect of these variables on the gross weight was considered in the analysis, as was the additional weight of the boundary-layer-control equipment. The effect of the additional weight of the boundary-layer-control equipment on the take-off performance characteristics was isolated by calculating the take-off performance characteristics of the boundary-layer-control airplane with and without the additional weight of the boundary-layer-control equipment included in the gross weight estimate. This calculation was made for wings of aspect ratio of 10 only since the effect would be relatively the same for other aspect ratios. In addition, for the boundary-layer-control airplane, the effect of variation in maximum lift coefficient on take-off distance was investigated for all configurations. The effects of boundary-layer control on the maximum and stalling speeds were also evaluated.

SYMBOLS

W	gross weight of airplanes, pounds
w	weight of airplane components, pounds
g	acceleration of gravity, feet per second^2
T	thrust, pounds
T_o	static thrust, pounds
$T_{V_{max}}$	thrust at maximum velocity, pounds
S	wing area, square feet
V	velocity, feet per second
D	airplane drag, pounds
C_{D_o}	wing profile-drag coefficient $\left(\frac{\text{Wing profile drag}}{\frac{1}{2}\rho V_o{}^2 S}\right)$
C_D	airplane drag coefficient $\left(\frac{D}{\frac{1}{2}\rho V_o{}^2 S}\right)$
C_L	airplane lift coefficient $\left(\frac{W}{\frac{1}{2}\rho V_o{}^2 S}\right)$
C_{D_i}	induced drag coefficient $\left(\frac{C_L{}^2}{\pi Ae}\right)$
s_t	total take-off distance, feet
s_g	ground-run distance, feet
q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
H	absolute total pressure, pounds per square foot
C_p	pressure coefficient $\left(\frac{H_o - H_d}{q_o}\right)$

Q	quantity rate of flow, cubic feet per second
C_Q	quantity rate of flow coefficient $\left(\frac{Q}{SV_o}\right)$
P	brake horsepower
A	aspect ratio $\left(\frac{b^2}{S}\right)$
h	altitude at which take-off is assumed completed (50 feet)
b	span, feet
e	wing efficiency factor based on variation of spanwise loading from an elliptical loading with no ground effect
t	wing root thickness, feet

$$\left.\begin{aligned} A_P &= \frac{T_o}{P} \\ B &= \frac{2(T - T_o)}{P\rho V^2} \\ C &= \frac{T_{V_{max}}}{P} \end{aligned}\right\} \text{Constants for calculating propeller thrust}$$

η	efficiency factor of blower (assumed 0.9)
μ	ground-friction coefficient
ρ	mass density of air, slugs per cubic foot
θ	angle with respect to the horizontal of flight path during climb
γ	ratio of specific heats at constant volume and constant pressure ($\gamma = 1.4$ for air)

Subscripts

c	conventional airplane
BLC	boundary-layer-control airplane

o	free-stream conditions
t	conditions at take-off of airplane
l	conditions during ground run of airplane
d	conditions in boundary-layer-control duct
b	blower
bm	blower engine
s	stalling condition
max	maximum conditions
opt	optimum conditions
u	pay load

METHOD OF ANALYSIS

In calculating the take-off performance characteristics for the various airplanes in this analysis, a number of basic assumptions were made concerning the airplane configurations, the aerodynamic characteristics of the wing both with and without boundary-layer control, the method of estimating the weight of the airplane and the auxiliary boundary-layer-control equipment, and the method used in performing the take-off maneuver. The final comparative results of the analysis will not be affected by the assumptions if the same assumptions are used for both the conventional and boundary-layer-control airplanes, as was done herein except for the assumptions concerning the weight of the boundary-layer equipment which, in this instance, were conservative. In general, the assumptions were compatible with data from existing airplanes.

Assumptions

Airplane configuration.- The airplane was assumed to have a cantilever semimonocoque wing, rectangular in plan form, with airfoil sections tapering from a thickness-chord ratio of 0.18 at the root to 0.12 at the tip. The fuselage and retractable landing gear were constant in size with the fuselage frontal area F determined from the fixed pay load w_u of 1500 pounds by the following relation of reference 4:

$$F = 0.15 w_u^{2/3}$$

The empennage area was taken as 25 percent of the wing area.

The propeller was considered to be fully automatic and to permit development of full engine speed and power at all airspeeds. Sufficient fuel and oil for 5 hours of cruising at 60-percent full power were assumed.

The boundary-layer control was assumed to be obtained by an auxiliary engine and blower located in the fuselage to provide suction for the boundary-layer control slots on the wings. The internal spaces of the semimonocoque wings were to act as ducts to lead the air from the slots to the blower.

Aerodynamic characteristics.- The profile-drag coefficients of the wing with and without boundary-layer control were obtained by use of section data given in references 5, 6, 7, and 8 and are given in figure 1. The empennage drag coefficient used was 0.01 based on empennage area while the fuselage and landing-gear drag coefficients were 0.20 and 0.05, respectively, based on fuselage frontal area (reference 9). The induced drag coefficients were calculated from the expression

$$C_{D_i} = \frac{{C_L}^2}{\pi Ae}$$

where e was assumed to be 0.9. The maximum attainable lift coefficients were assumed to be 2.8 and 5.0 for the airplanes without and with boundary-layer control, respectively.

Weight analysis.- In the analysis of the take-off characteristics of the assumed airplanes, it was found convenient to take the span, aspect ratio, and power as the independent variables, since the gross weight is dependent on these variables. It was necessary, therefore, to find a relation giving gross weight as a function of span, aspect ratio, and power. This relation was found by determining the weights of various airplane components as functions of one or more of the variables. These components are symbolized by the following subscripts:

m engine

p propeller, hub, and engine auxiliaries

g gasoline and oil

F fuselage

L landing gear

E empennage

w wing

The following empirical relations giving the weights of engine, engine auxiliaries, propeller, and hub were determined from an analysis of 65 airplanes and 225 engines ranging from 50 to 2000 horsepower (references 9 and 10)

$$w_m = P\left(\frac{192}{P - 30} + 1.1\right) \tag{1}$$

$$w_p = P\left(\frac{4.58}{P^{0.68}} + 0.48\right) \tag{2}$$

The airplane was assumed to have a cruising duration of 5 hours at 60 percent full power with a specific fuel consumption of 0.5 pound per horsepower per hour and an oil requirement of one gallon per 16 gallons of gasoline (reference 9). Thus, the weight of gasoline and oil is

$$w_g = 1.62P \tag{3}$$

The empirical relations giving the weight of fuselage, landing gear, empennage, and wing are from reference 9 and are as follows:

$$w_F = 0.172W^{0.94} \tag{4}$$

$$w_L = 0.067W^{0.98} \tag{5}$$

$$w_E = 0.25S \tag{6}$$

$$w_w = 0.0465A^{0.47}\left(\frac{W}{b}\right)^{0.53}\left(\frac{b}{t}\right)^{0.115} \tag{7}$$

For the analysis, a value of $\frac{b}{t} = 35$, which is a representative value for the type airplane considered, was assumed in evaluating equation (7). The ratio of span to root thickness b/t enters in the wing weight equation to the 0.115 power and, since the wing weight is only approximately 15 percent of the gross weight, this ratio could vary appreciably without causing a change in the gross weight estimate of more than 1 to 2 percent.

A summation of equations 1 to 7 plus the assumed pay load of 1500 pounds results in the following empirical relation giving the gross

weight of the conventional airplane as a function of span, aspect ratio, and horsepower:

$$W_c = P\left[\frac{192}{P - 30} + \frac{4.58}{P^{0.68}} + 3.20\right] + 1500 + 0.172W^{0.94} + 0.067W^{0.98}$$

$$+ S\left[0.25 + 0.07A^{0.47}\left(\frac{W}{b}\right)^{0.53}\right] \tag{8}$$

The gross weight of the boundary-layer-control airplane is then the gross weight of the conventional airplane plus the gross weight of the blower engine w_{bm} and blower w_b, that is:

$$W_{BLC} = W_c + w_{bm} + w_b \tag{9}$$

The estimate of the blower-engine power was made in terms of the compression ratio, quantity flow, absolute entrance pressure, and blower efficiency by the following expression for an adiabatic gas flow:

$$P_{bm} = \frac{\frac{\gamma}{\gamma - 1} H_d Q}{550\eta}\left[\left(\frac{H_o}{H_d}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{10}$$

Reference 2 indicated that sufficient boundary-layer control for a maximum lift coefficient of 5.0 could be obtained with a flow coefficient $C_Q \doteq 0.03$ and a pressure coefficient $C_P = 4.0$. However, in order to make a conservative estimate of the weight of the boundary-layer-control equipment, a flow coefficient of 0.04 and a pressure coefficient of 15.0 were used and, by substitution, equation 10 becomes, for $\eta = 0.9$,

$$P_{bm} = 0.00367\left(H_o - 3\frac{W}{S}\right)\sqrt{WS}\left[\left(\frac{H_o}{H_o - 3\frac{W}{S}}\right)^{0.286} - 1\right] \tag{11}$$

The blower engine weight is then obtained by assuming an engine weight of 2.5 pounds per horsepower and a flight duration of 5 hours at 60-percent power with a specific fuel consumption of 0.5 pound per horsepower per hour. With these assumptions, the blower engine weight, including fuel, is:

$$w_{bm} = 4P_{bm} = 0.0147\left(H_o - 3\frac{W}{S}\right)\sqrt{WS}\left[\left(\frac{H_o}{H_o - 3\frac{W}{S}}\right)^{0.286} - 1\right] \qquad (12)$$

The weight of the blower was obtained by assuming an axial-flow stator-rotor type constructed of aluminum alloy having a hub-to-tip ratio of 0.6 and an axial velocity of 400 feet per second. The outer casing was assumed to be $\frac{1}{8}$ inch thick and 48 inches long; the rotor, blade, and shaft to be equivalent to a disk 2 inches thick with a diameter 0.8 of the tip diameter; and the stator vanes to be equivalent to a disk $\frac{1}{4}$ inch thick with the same diameter as the complete rotor. With these assumptions, the blower-weight equation was developed and is as follows:

$$w_b = 0.044\sqrt{WS} + 1.13(WS)^{0.25} \qquad (13)$$

Take-off maneuver.- The take-offs were assumed to be made at full power, with no headwind, and to consist of three phases: (1) an accelerated run on the ground at the attitude for least total resistance until the speed for take-off was reached; (2) the transition arc or period of change of the flight path from ground run to steady climb; and (3) steady climb to an altitude of 50 feet where take-off is considered complete.

Method of Calculation

Total take-off distance.- The total take-off distance was calculated for a range of maximum lift coefficients up to 5.9 for the boundary-layer-control airplanes and for a maximum lift coefficient of 2.8 for the conventional airplanes over a range of horsepower from 200 to 1300, span from 30 to 100 feet, and aspect ratio from 5 to 15. The following equation for the total take-off distance was obtained from reference 11 by combining the expressions giving the distance required for ground run, transition arc, and climb:

$$s_t = \frac{W/S}{\rho g}\left\{\frac{1}{\left(\mu C_{L_1} - C_{D_1}\right) - B\frac{W/S}{W/P}}\log_e\left[1 + \frac{\left(\mu C_{L_1} - C_{D_1}\right) - B\frac{W/S}{W/P}}{\left(\frac{A_P}{W/P} - \mu\right)C_{L_t}}\right] + \frac{2\tan\frac{\theta}{2}}{C_{L_{max}} - C_{L_t}} + \frac{\rho g h}{\frac{W}{S}\tan\theta}\right\} \qquad (14)$$

where

$$\theta = \sin^{-1}\left[\frac{A_P}{W/P} - \left(B\frac{W/S}{W/P} + C_{D_t}\right)\frac{1}{C_{L_t}}\right] \tag{15}$$

and

$$C_{L_t} = 0.9C_{L_{max}}$$

which is the usual value assumed for C_{L_t} in an analysis of this nature.

The attitude of least air and ground resistance during the ground run, as shown in reference 12, is defined by the expression:

$$C_{L_1} = \frac{1}{2}\mu\pi Ae \tag{16}$$

In using equation (16) in the analysis, the profile-drag variation is neglected. The assumed ground friction coefficient $\mu = 0.2$ is equivalent to that of deep grass or sand. A lower value of μ corresponding to that of concrete would reduce the take-off distance of both the conventional and boundary-layer-control airplanes by approximately the same percentage; thus the comparative results would be equal to those given in this paper.

The power constants A_P and B used in these equations were obtained from reference 11 and are reproduced herein as figure 2. Use of figure 2 requires determination of V_{max} as a function of span by equating thrust to airplane drag as follows:

$$T_{V_{max}} = \frac{1}{2}\rho V_{max}^2 \frac{b^2}{A}C_D \tag{17}$$

where C_D is the summation of the assumed drags of the airplane components in coefficient form. Also, from reference 11,

$$T_{V_{max}} = CP \tag{18}$$

where, from figure 2,

$$C = 3.09 - 0.005V_{max} \tag{19}$$

Equation (17) then becomes

$$P(3.09 - 0.005V_{max}) = \frac{1}{2}\rho V_{max}^2 \frac{b^2}{A}C_D$$

From this equation V_{max} as a function of span for various powers and aspect ratios was obtained for both the conventional and boundary-layer-control airplane, and the results are given in figures 3 and 4. Once V_{max} is obtained as a function of span, the power constants A_P and B are obtained for the various spans from figure 2.

Ground-run distance and stalling speed.- The ground run was calculated by use of the following expression from reference 11:

$$s_g = \frac{W/S}{\rho g\left[\left(\mu C_{L_1} - C_{D_1}\right) - B\frac{W/S}{W/P}\right]}\log_e\left[1 + \frac{\left(\mu C_{L_1} - C_{D_1}\right) - B\frac{W/S}{W/P}}{\left(\frac{A_P}{W/P} - \mu\right)C_{L_t}}\right] \tag{20}$$

Maximum lift coefficients of 2.8 and 5.0 were used for the conventional and boundary-layer-control airplanes, respectively. For aspect ratio of 5, however, because of the large induced drags resulting from the large lift coefficients, the power available was insufficient to maintain level flight when the lift coefficient was greater than 3.8; therefore, a maximum lift coefficient of 3.8 was used in calculating the ground run when the aspect ratio was 5.

The stalling speed V_s was found for each airplane from the relation

$$V_s = \sqrt{\frac{2W}{\rho S C_{L_{max}}}} \tag{21}$$

RESULTS AND DISCUSSION

The gross weight of the conventional airplane is shown in figure 5 as a function of the span for various horsepowers and an aspect ratio of 10. Similar plots not given were made for aspect ratios of 5 and 15. The gross weight of the boundary-layer-control airplane was found by adding the weights of the boundary-layer-control blower and motor obtained from plots similar to those given in figure 6 to the gross weight of the conventional airplane for corresponding spans, aspect ratios, and horsepowers. From the plots of maximum speed, as a function of span for the various horsepowers and aspect ratios, as presented in figures 3 and 4,

the maximum speed could be determined. These values of V_{max} for a given span were used to find the propeller constants, A_p and B, from figure 2. Since the gross weight and propeller characteristics were known, the performance equations (14), (20), and (21) were then evaluated to find the effects of variation of maximum lift coefficient, span, power, and aspect ratio on the take-off distance, ground run, and stalling speed.

Total Take-off Characteristics

Optimum lift coefficient.- The maximum lift coefficient attainable with conventional high-lift devices was assumed to be 2.8, and this value was used throughout the analysis for the conventional airplanes. With boundary-layer control, however, the take-off characteristics were calculated for a range of maximum lift coefficients up to 5.9 for the range of span, horsepower, and aspect ratio investigated to find the maximum lift coefficient that would produce the shortest take-off distance for each airplane configuration. Examples of the variations of total take-off distance of the boundary-layer-control airplane with maximum lift coefficient for various spans and horsepowers at an aspect ratio of 10 are presented in figure 7. For a given aspect ratio, the lift coefficient for minimum take-off distance increases as the span decreases and the wing loading increases. These results were cross-plotted in figure 8 to show the variation of optimum C_L with wing loading for the various aspect ratios and horsepowers. The figure shows that at an aspect ratio of 5, regardless of wing loadings, the optimum lift coefficient is less or slightly greater only than that available with conventional high-lift devices. For aspect ratios of 10 and 15 and wing loadings of less than 10 pounds per square foot, although the optimum maximum lift coefficient for take-off exceeds the maximum lift coefficient attainable without boundary-layer control, the use of lift coefficients greater than 2.8 will decrease the take-off distance very little. (See fig. 7.) For the larger wing loadings, however, the rate of change of the take-off distance with lift coefficient is large and the use of the optimum lift coefficient offers a considerable decrease in take-off distance.

Throughout the remainder of the analysis, the effects of other variables on total take-off distance are discussed for the optimum lift coefficient unless it exceeds 5.0, in which case the take-off distance was calculated for a maximum lift coefficient of 5.0.

Effect of boundary-layer control on take-off.- The variation of take-off distance with span for various horsepowers is presented for aspect ratios of 5, 10, and 15 in figures 9 and 10 for the conventional and boundary-layer-control airplanes, respectively. The effect of the weight of the boundary-layer-control equipment on the take-off characteristics was found for an aspect ratio of 10 by assuming that no weight

was added by the auxiliary blower and motor. These data are presented in figure 11.

The effect of boundary-layer control on the total take-off distance of the airplane may be seen in figure 12 which shows the total take-off distance as a function of maximum speed for both the conventional and boundary-layer-control airplanes with varying aspect ratio and horsepower. Figure 12 shows that for a given maximum speed and an aspect ratio of 5, regardless of span, the boundary-layer-control airplane generally requires more distance for take-off than the conventional airplane. As the aspect ratio increases, however, boundary-layer control becomes more effective, and for an aspect ratio of 10 or more with a wing loading of 10 pounds per square foot or more the addition of boundary-layer control decreases the total take-off distance. It follows that, for a given take-off distance, the boundary-layer-control airplane would have a greater maximum speed.

The effect of the weight of the boundary-layer-control equipment on the total take-off distance is shown in figure 12(b) for aspect ratio of 10. This figure shows that the total take-off distance may be decreased appreciably by decreasing the weight; therefore, every effort should be made to decrease the weight of the boundary-layer-control equipment.

Figure 12 also shows that the absolute minimum total take-off distance obtained with a low wing loading and moderately low aspect ratio is not decreased by the addition of boundary-layer control.

Effect of power loading on take-off distance.- The power loading is shown as a function of take-off distance for various wing loadings and aspect ratios in figures 13 and 14 for the conventional and boundary-layer-control airplanes, respectively. As is shown, the optimum power loading, which is nearly independent of wing loading and aspect ratio, is approximately 8.5 and 9.0 pounds per horsepower for the conventional airplane and the boundary-layer-control airplane, respectively. It should be noted that increasing the horsepower above the optimum value increases the take-off distance. This result is due to the accompanying change in engine, fuel, and structural weight.

Ground-Run and Stalling-Speed Characteristics

In order to obtain the minimum ground run, which is given in figures 15 and 16, the calculations were made by considering the ground run completed when a speed was reached corresponding to a flying speed at 0.9 of the assumed maximum lift coefficient. During the analysis, it was found that, because the induced drags were large for aspect ratio of 5 of the boundary-layer-control airplane, the power was insufficient to maintain level flight at lift coefficients greater than 3.8; therefore,

the ground run for aspect ratio of 5 was calculated for a maximum lift coefficient of 3.8. The variation of ground run with span for various horsepowers and aspect ratios is shown in figures 15 and 16 for the conventional and boundary-layer-control airplanes, respectively, and in figure 17 for the airplane with boundary-layer control but with the weight of the additional equipment disregarded. These data are compared in figure 18 where the ground run has been plotted as a function of V_{max} for various horsepowers and aspect ratios.

The boundary-layer-control airplane had shorter ground runs than the conventional airplane for all configurations considered. The reduction was negligible for an aspect ratio of 5 and a maximum lift coefficient of 3.8. At aspect ratios of 10 and 15 and maximum lift coefficient of 5.0, however, the ground run was decreased 10 to 30 percent by the addition of boundary-layer control. The beneficial effect of reducing the boundary-layer-control-equipment weight, as previously noted for the total take-off distance, was again observed for the case of the ground run (fig. 18(b)).

This reduced ground run produced by use of high maximum lift coefficients associated with boundary-layer control may prove to be most advantageous for carrier-based airplanes or seaplanes.

The stalling speed V_s is presented as a function of maximum speed in figure 19 for various aspect ratios and horsepowers. The stalling speed was 20 to 25 percent less for the boundary-layer-control airplane than for the conventional airplane for all configurations considered.

Effect of Assumptions on Results

Three assumptions were made, the effects of which should be considered in comparing the performance characteristics of the conventional and boundary-layer-control airplanes. These assumptions were:

(1) No head wind
(2) No ground effect
(3) A ratio of span to root thickness of 35 and a thickness to chord ratio of 0.18 at the root and 0.12 at the tip

These three assumptions would probably have a greater effect on the boundary-layer-control airplane than on the conventional airplane for the following reasons.

Head wind.- Because the maximum lift coefficients of the boundary-layer-control airplanes were greater than those of the conventional airplanes, the horizontal speed during the take-off maneuver was less

for the boundary-layer-control airplane than for the conventional airplane. Given a uniform head wind, the airspeeds of the two airplanes would remain unchanged, but the horizontal speed with respect to the ground of the slower airplane would be reduced by a greater percentage than that of the faster airplane. Therefore, the horizontal distance required to take off and climb to a given altitude would be decreased in a head wind by a greater percentage for the boundary-layer-control airplane than for the conventional airplane.

Ground effect.- The effect of proximity to the ground is mainly that of increasing the effective aspect ratio. The greater aspect ratio would result in proportionately greater decreases in induced drag for the boundary-layer-control airplane with its high maximum lift coefficient than for the conventional airplane; therefore the take-off distance for the boundary-layer-control airplane would be decreased by a greater percentage than that for the conventional airplane. For a more thorough treatment of this subject, see reference 13.

Wing thickness-chord ratios.- If the ratio of wing span to root thickness were maintained at 35, the root thickness-chord ratios of the wing would greatly exceed 0.18 for the larger spans and aspect ratios. The wing profile drag of the conventional airplane would, therefore, be considerably greater than the values used because of the large profile drags associated with airfoil sections having thickness ratios greater than 0.21 (reference 14). With boundary-layer control, however, it is possible to use the thicker airfoil sections without greatly increasing the profile drag; as experimental results have indicated that, when separated flow exists, the drag of an airfoil section, including the boundary-layer-control power, may be less than the drag without boundary-layer control (references 2, 7, and 8).

CONCLUSIONS

An analysis was made of the take-off characteristics of a liaison-type airplane with and without boundary-layer control capable of carrying a pay load of 1500 pounds and operating from small makeshift airports. The following conclusions may be drawn concerning the effects of boundary-layer control on the total take-off and ground-run distances, and stalling-speed characteristics of the type airplane investigated:

1. The addition of boundary-layer control does not reduce the absolute minimum total take-off distance which is obtained with a low wing loading and a moderately low aspect ratio.

2. The effectiveness of boundary-layer control in reducing the total take-off distance for a given maximum speed improves with increasing aspect ratio and, for wing loadings of 10 pounds per square foot or more

and an aspect ratio of 10 or more, the addition of boundary-layer control results in a decrease in the total take-off distance.

3. For a given maximum speed the ground run was reduced for all configurations by the use of boundary-layer control. This reduction was negligible for aspect ratio of 5 but was from 10 to 30 percent for aspect ratios of 10 and 15.

4. For a given maximum speed, the use of boundary-layer control resulted in a reduction in stalling speed of 20 to 25 percent for all configurations.

5. A reduction in the weight of the boundary-layer-control equipment would result in an appreciable decrease in the total take-off and ground-run distances but in a negligible decrease in stalling speed.

6. The optimum horsepower loading for minimum take-off distance was found to be approximately 8.5 and 9.0 pounds per horsepower for the conventional and boundary-layer-control airplanes, respectively.

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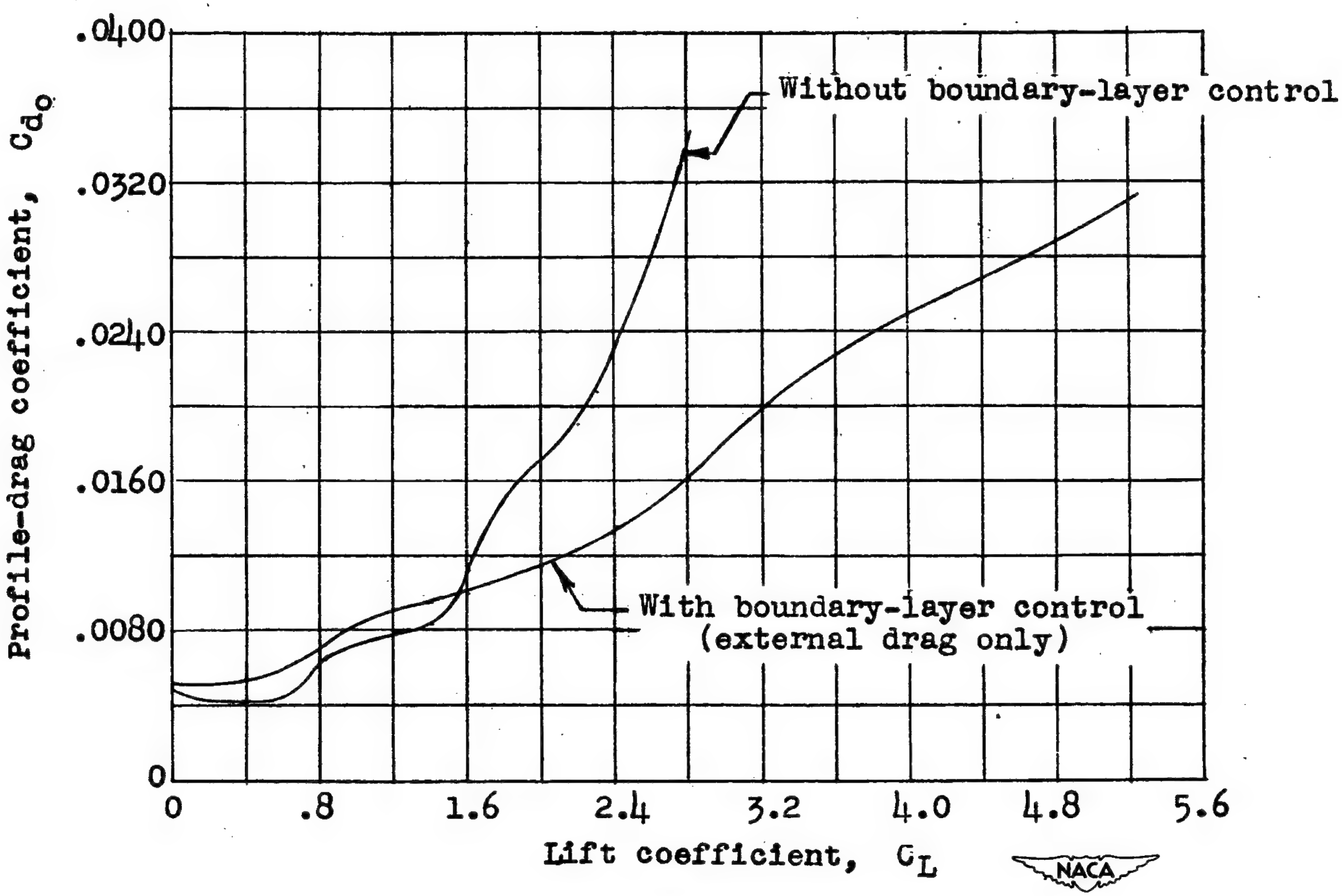


Figure 1.- Assumed profile-drag coefficient of the wing with and without boundary-layer control.

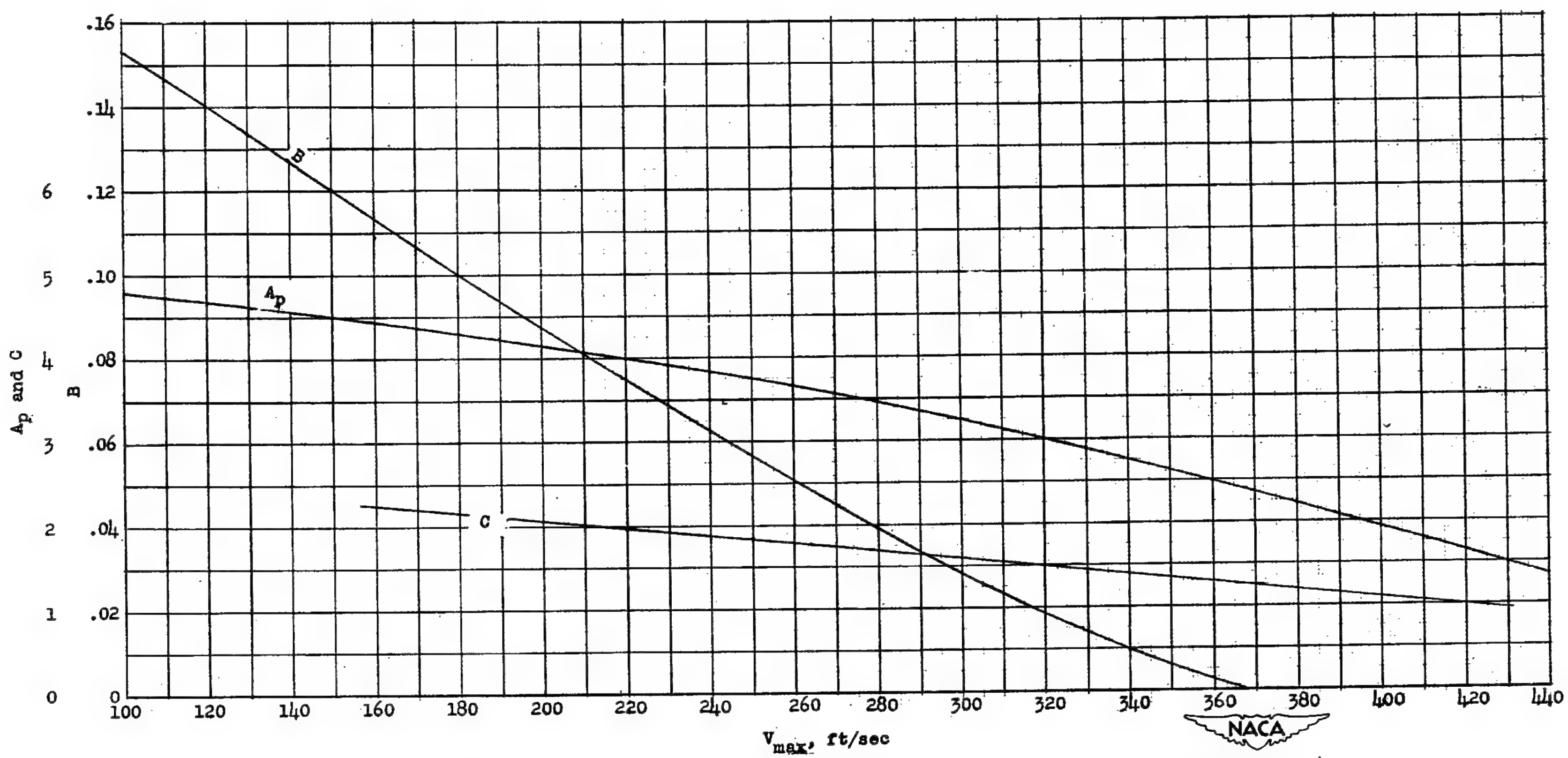
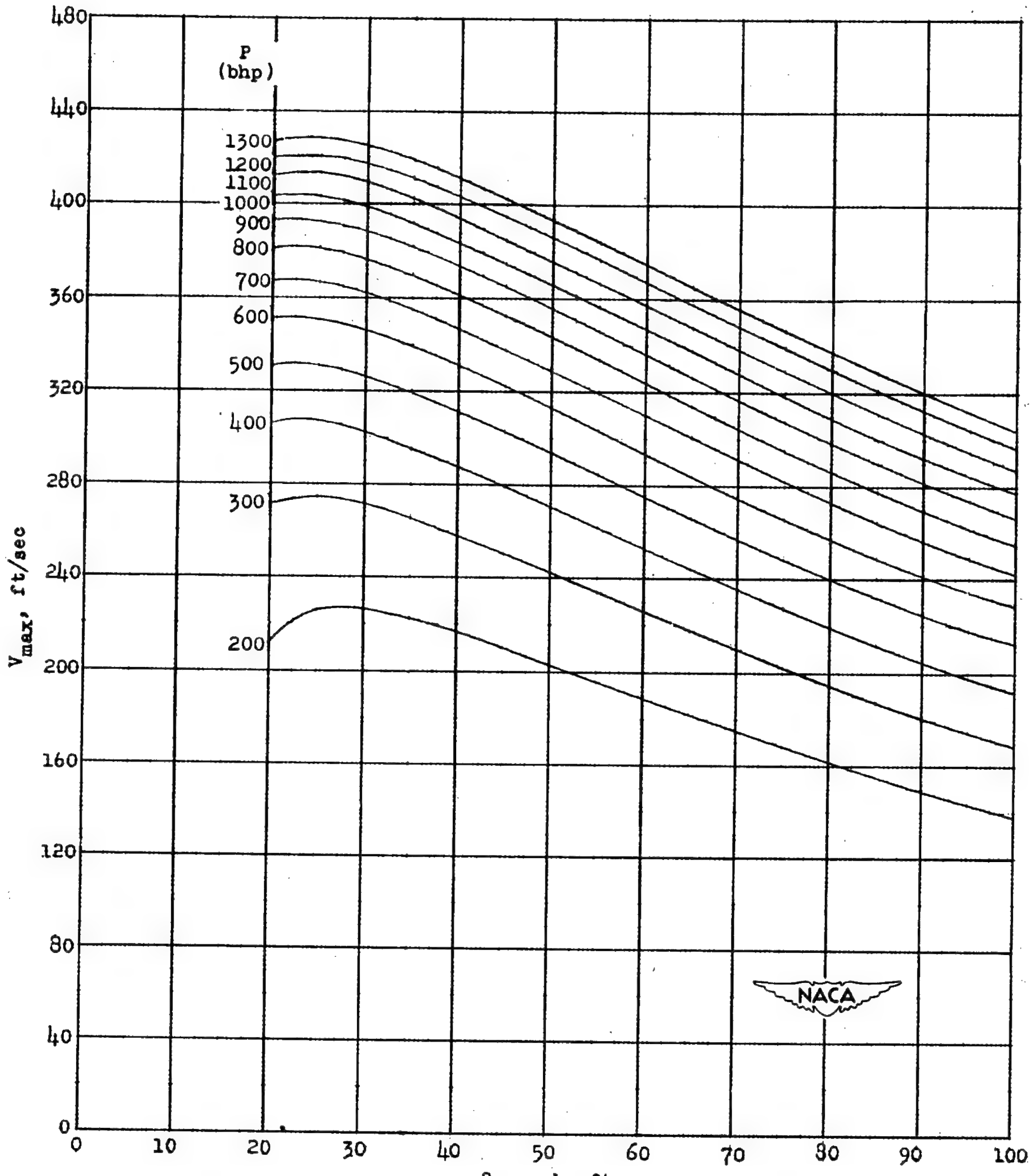
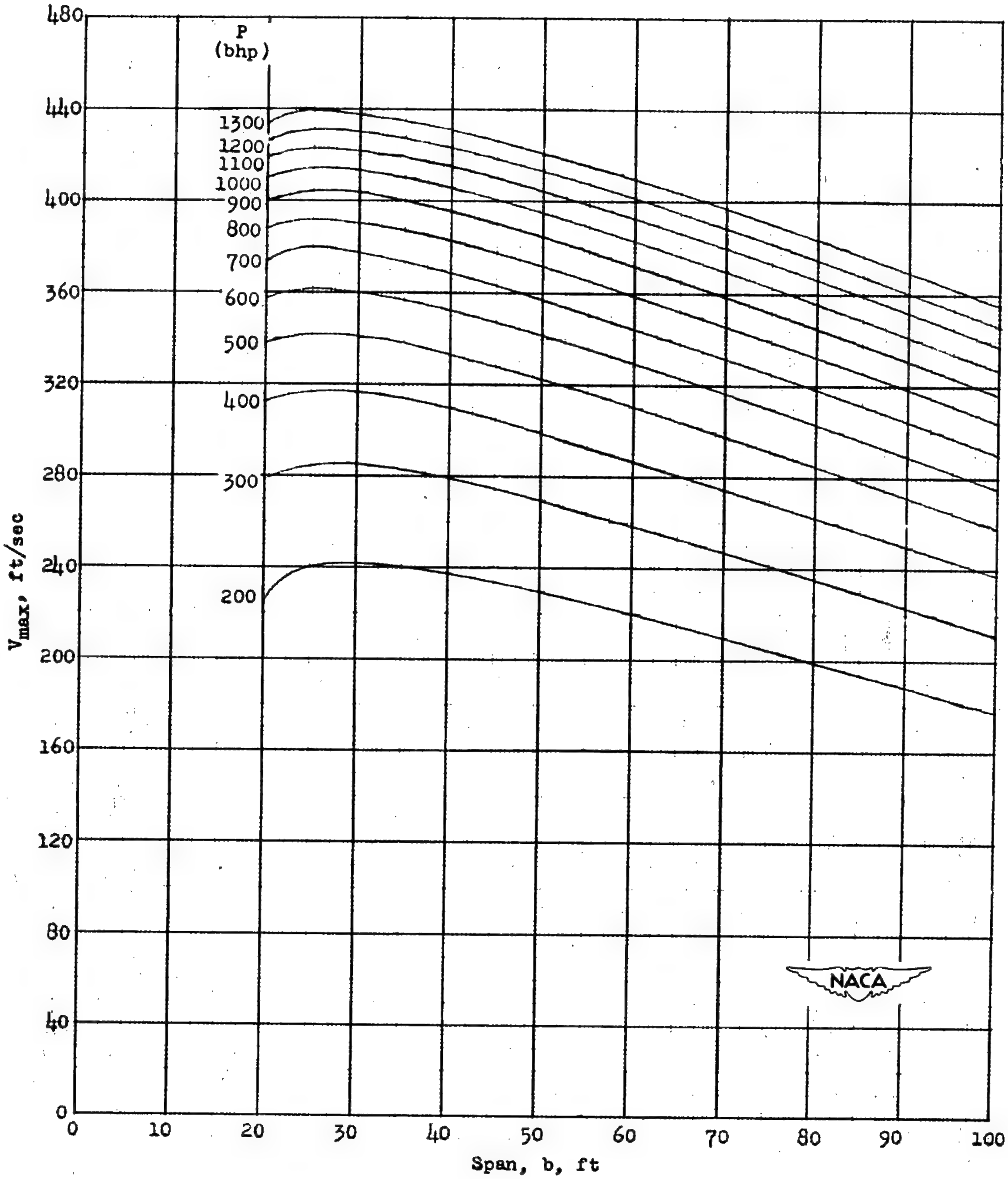


Figure 2 .- Thrust factors as functions of maximum speed for automatic propellers (reference 12).



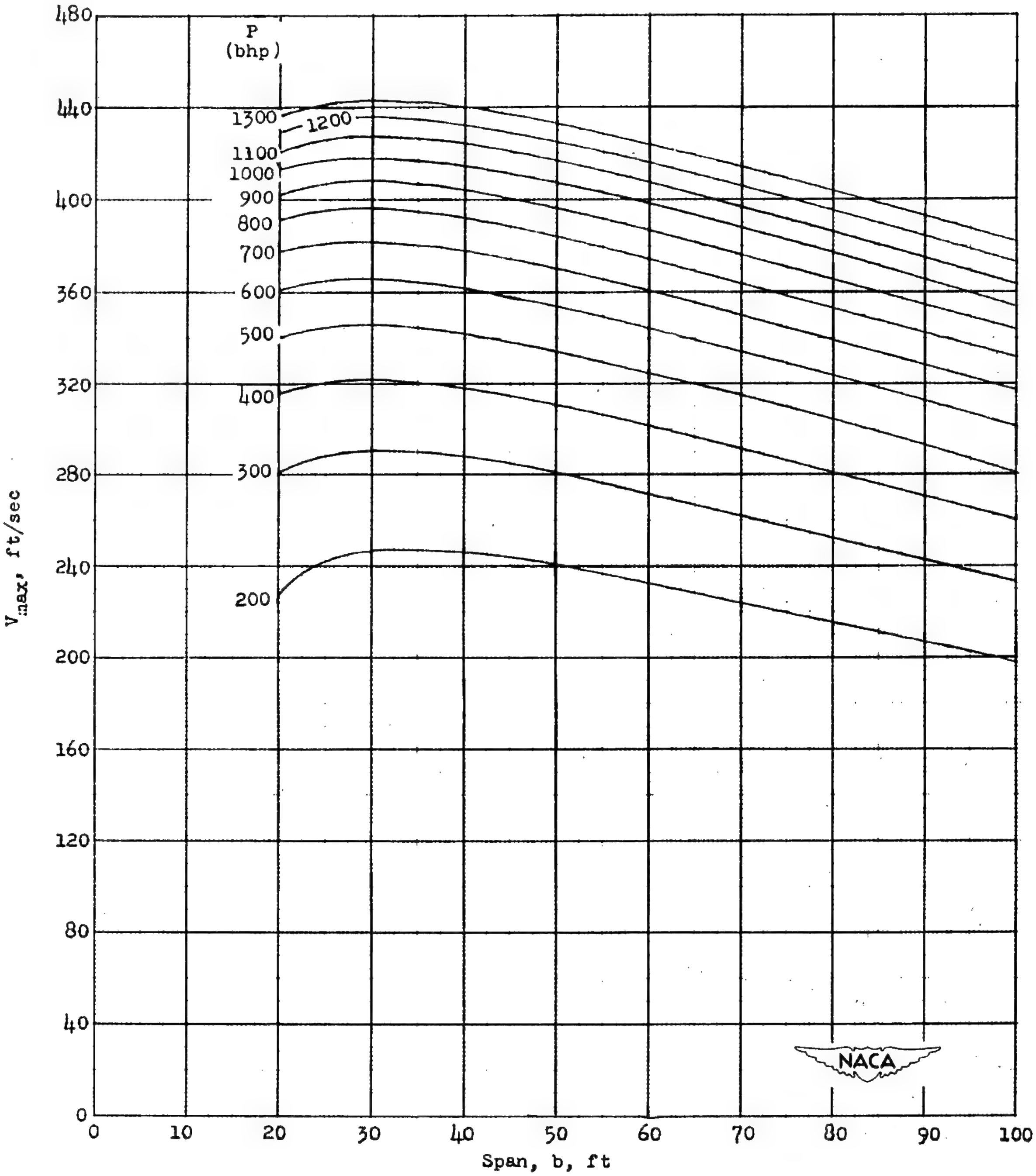
(a) A = 5.

Figure 3.- Maximum speed of assumed airplane without boundary-layer control as a function of span for various powers.



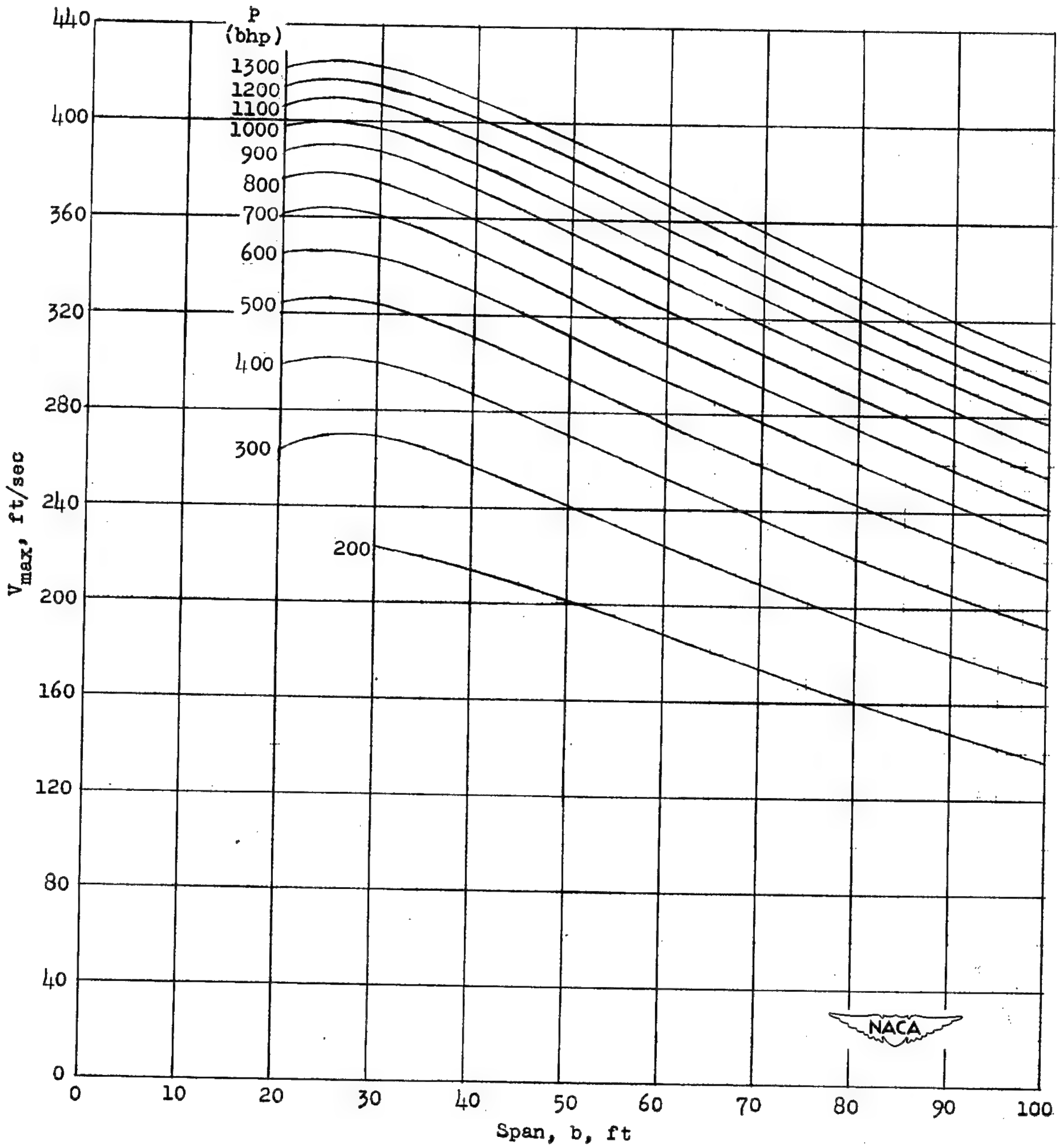
(b) A = 10.

Figure 3 .- Continued.



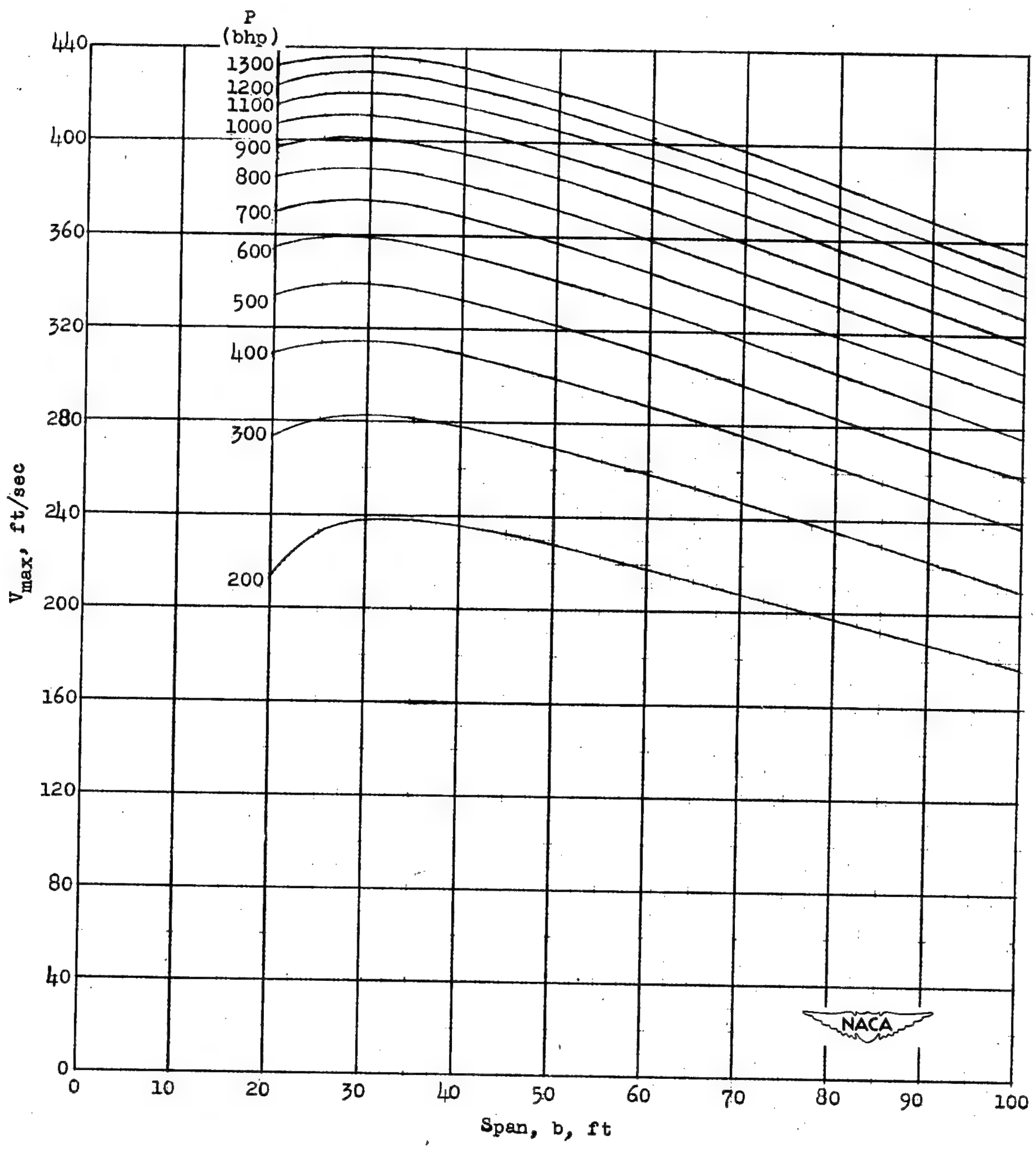
(c) A = 15.

Figure 3 .- Concluded.



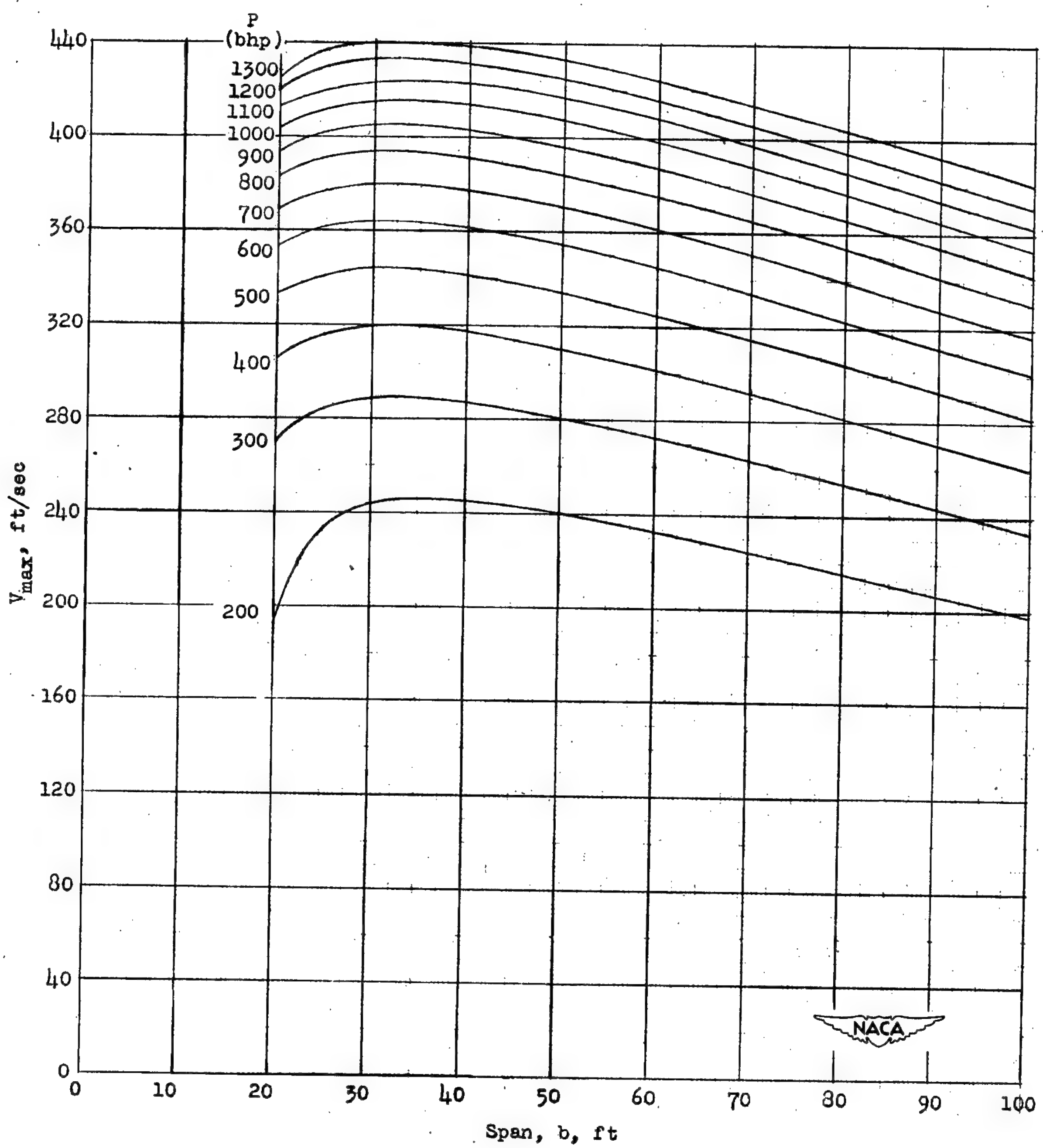
(a) A = 5.

Figure 4.- Maximum speed of assumed airplane with boundary-layer control as a function of span for various powers.



(b) A = 10.

Figure 4 .- Continued.



(c) A = 15.

Figure 4 .- Concluded.

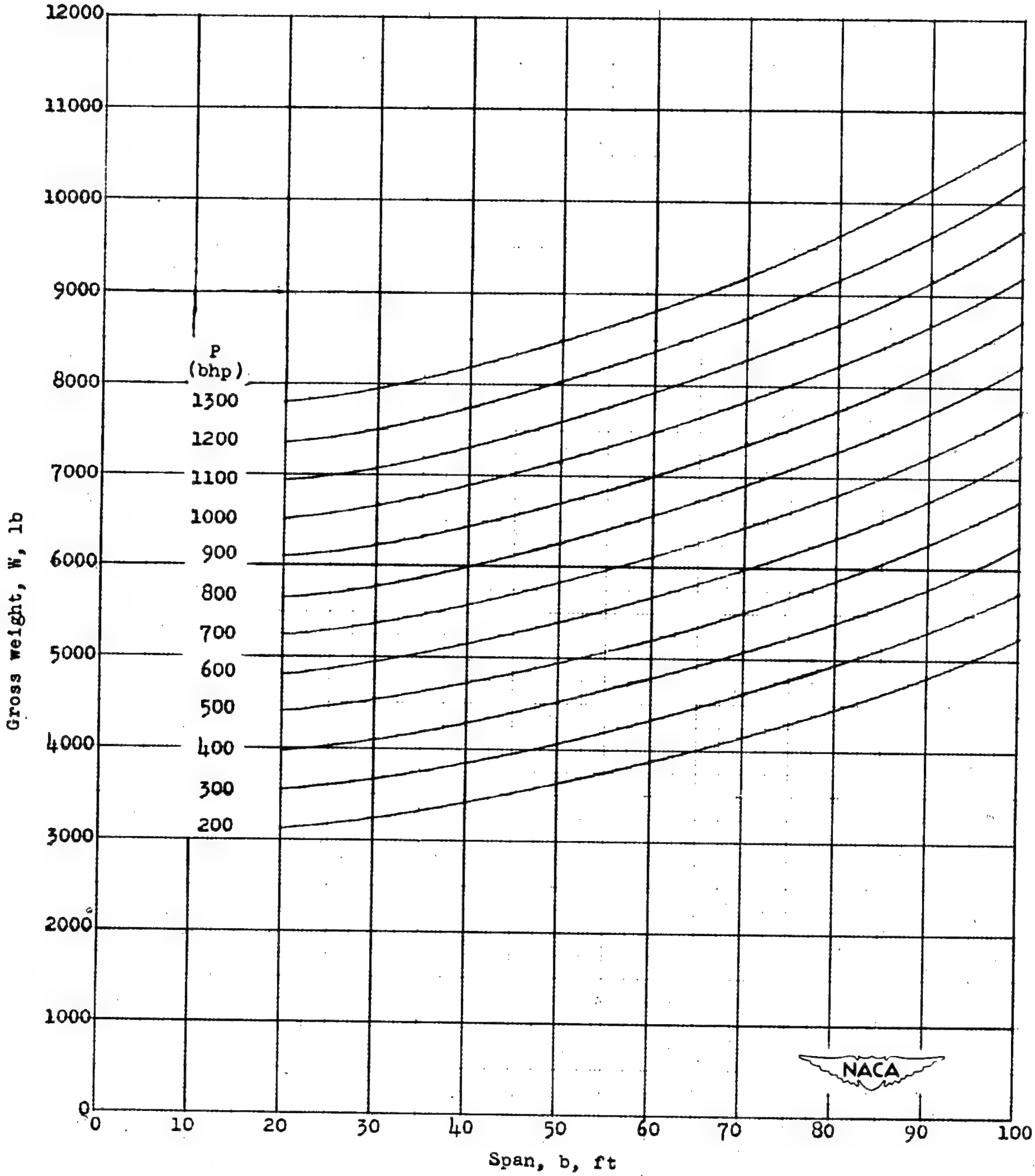
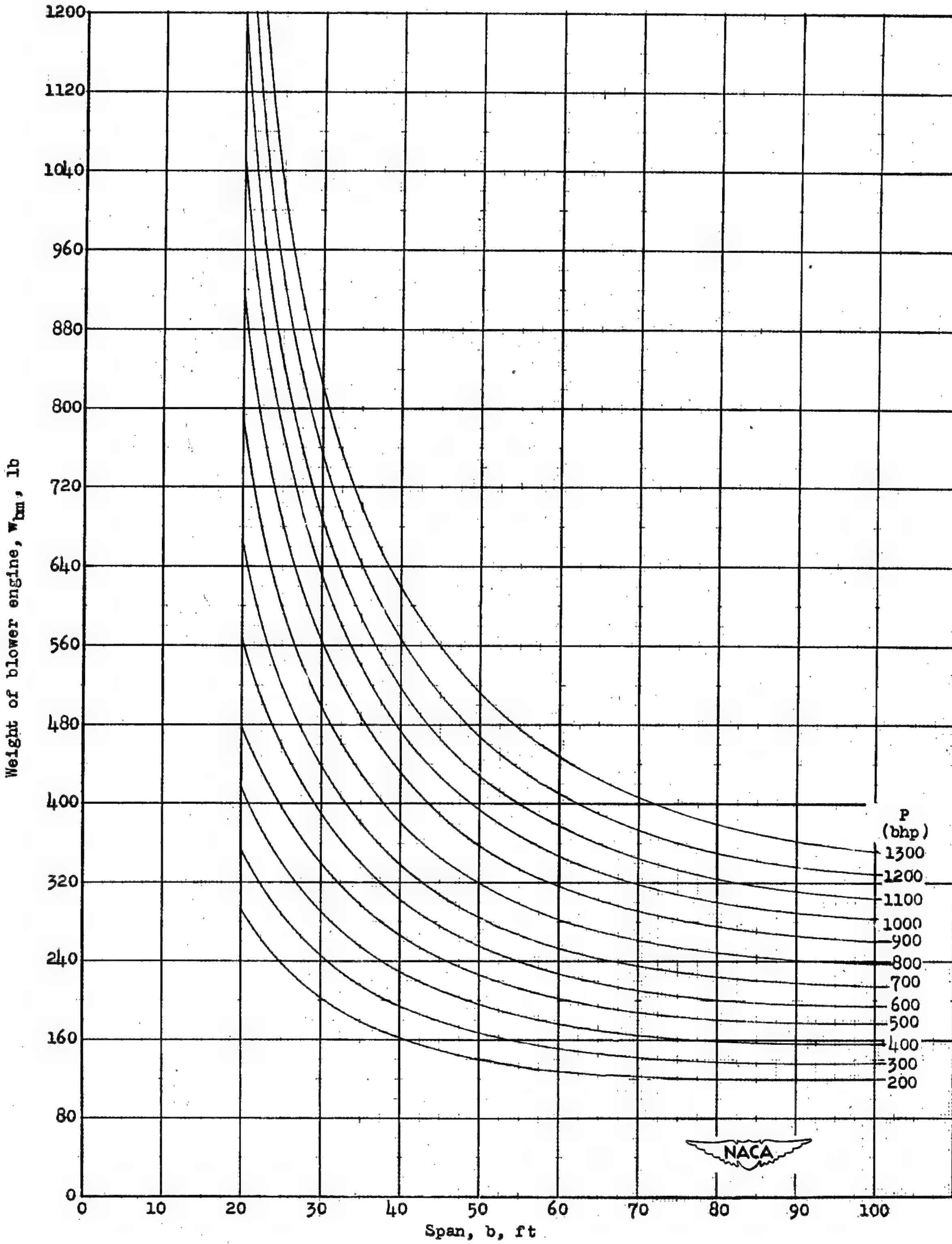
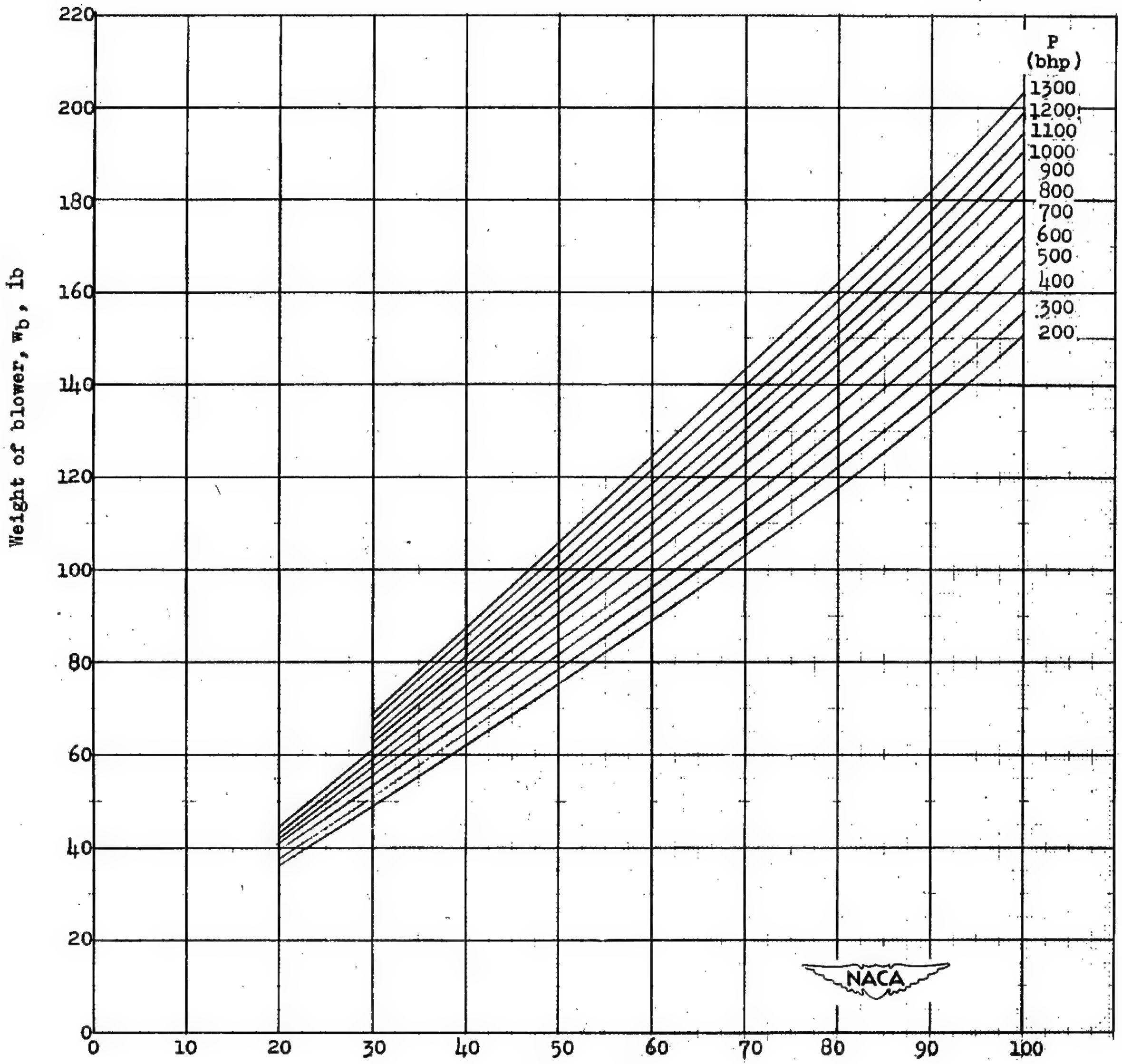


Figure 5.- Gross weight of conventional airplane as a function of span for various powers.
A = 10.



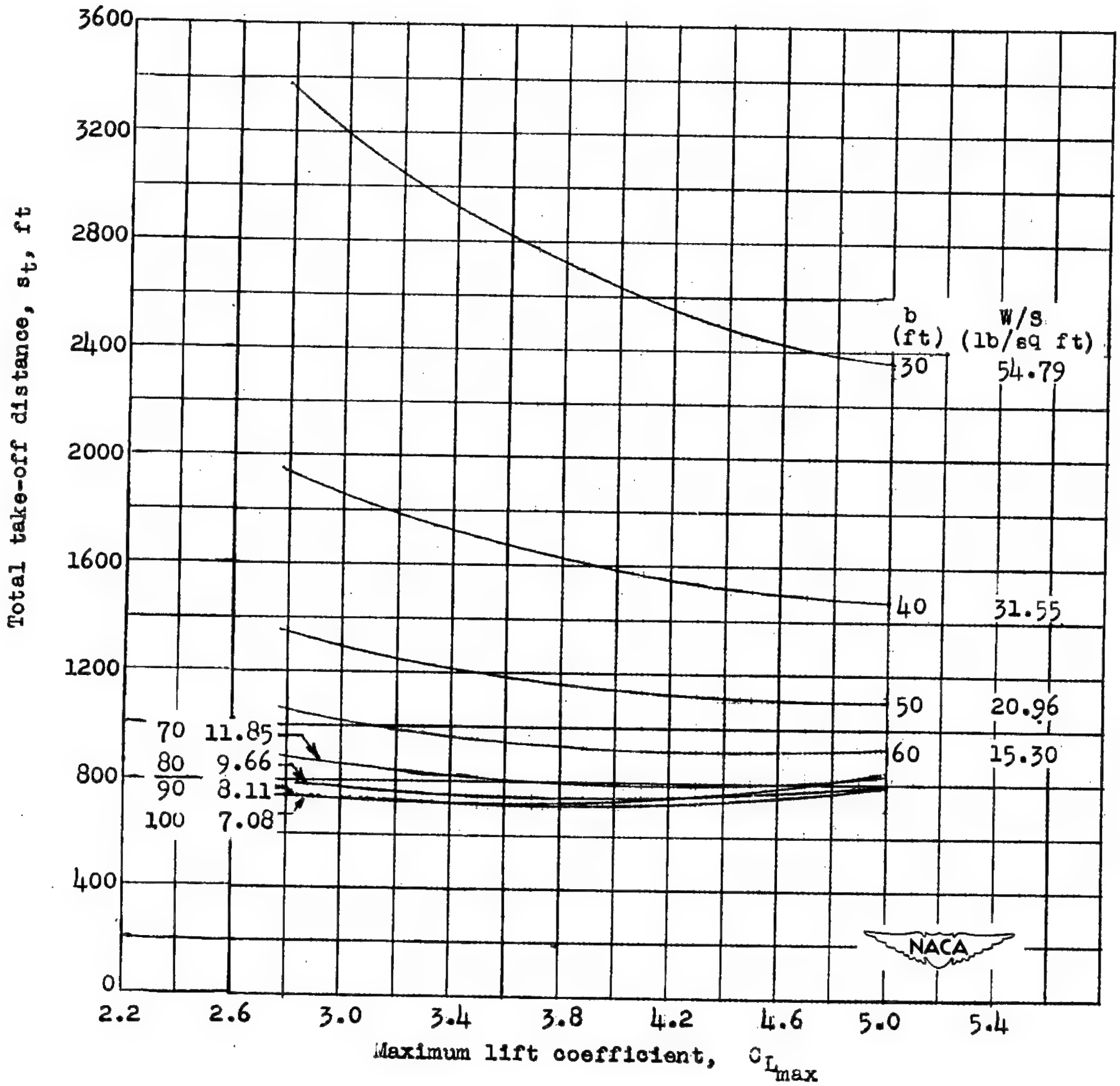
(a) Weight of blower engine.

Figure 6.- Weight of boundary-layer control equipment as a function of span for various main engine powers. A = 10.



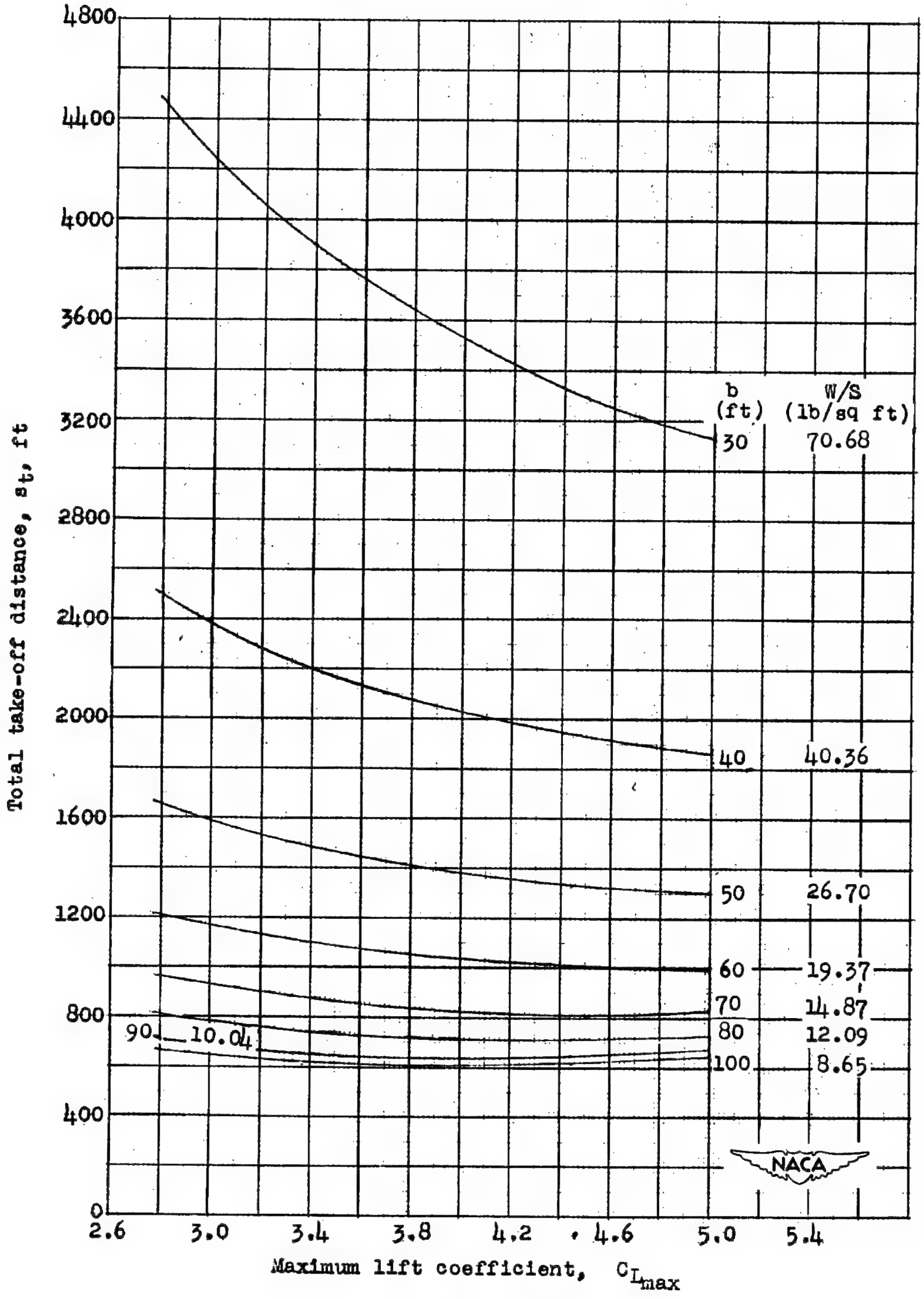
(b) Weight of blower.

Figure 6.- Concluded.



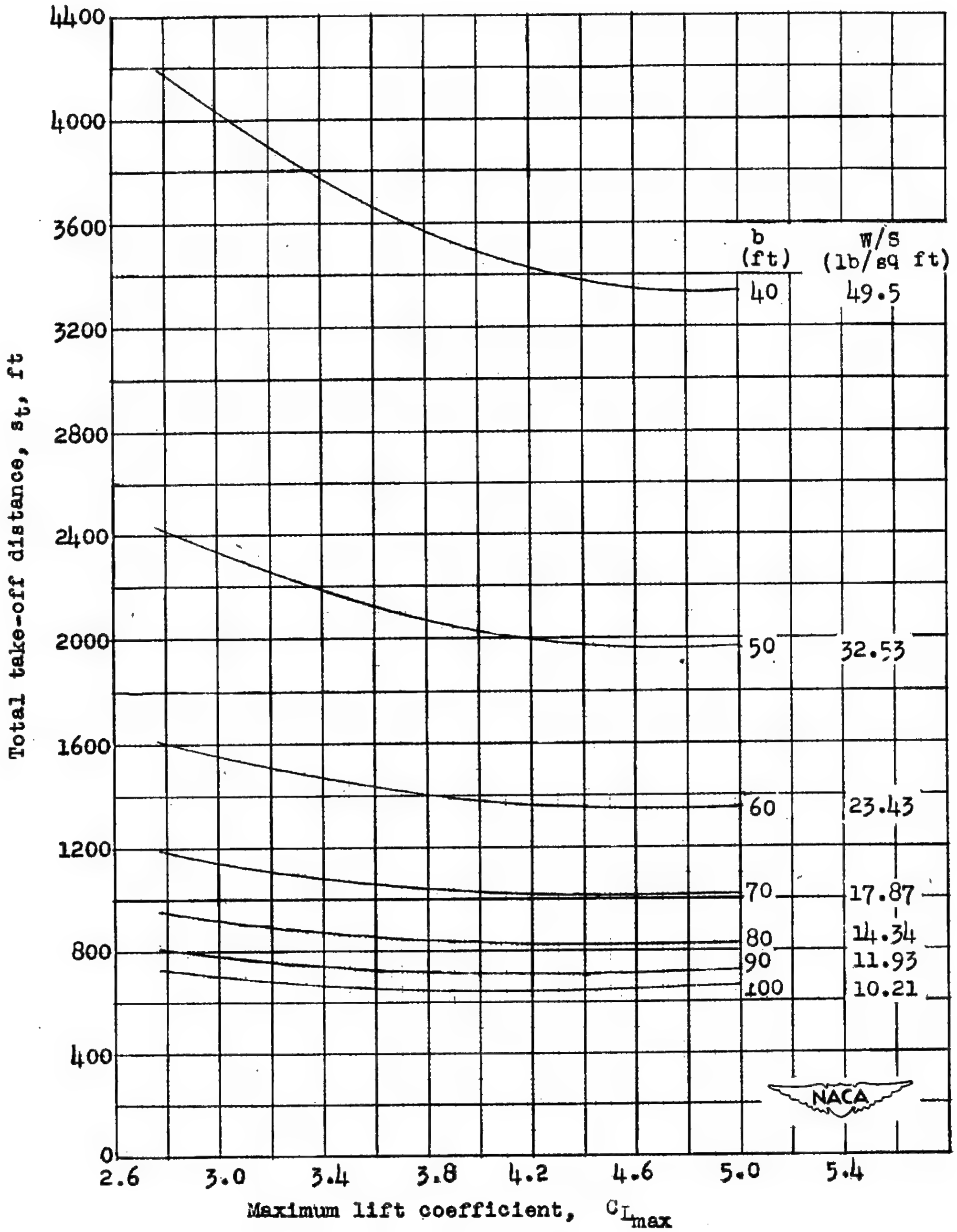
(a) $P = 500$ bhp.

Figure 7.- Total take-off distance of an airplane with boundary-layer control as a function of maximum lift coefficient for various spans and wing loadings. $A = 10$.



(b) P = 800 bhp.

Figure 7 .- Continued.



(c) P = 1100 bhp.

Figure 7 .- Concluded.

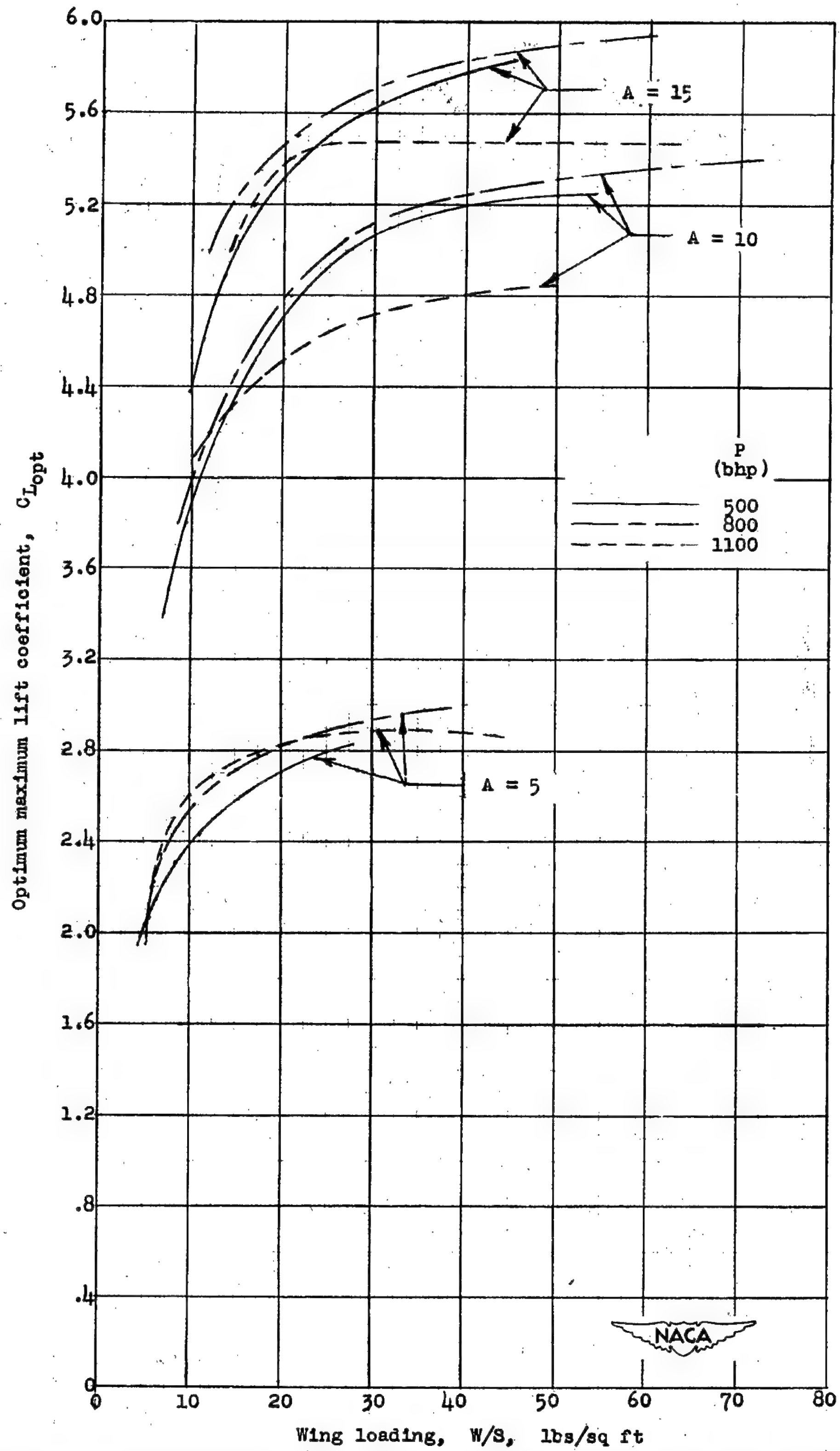
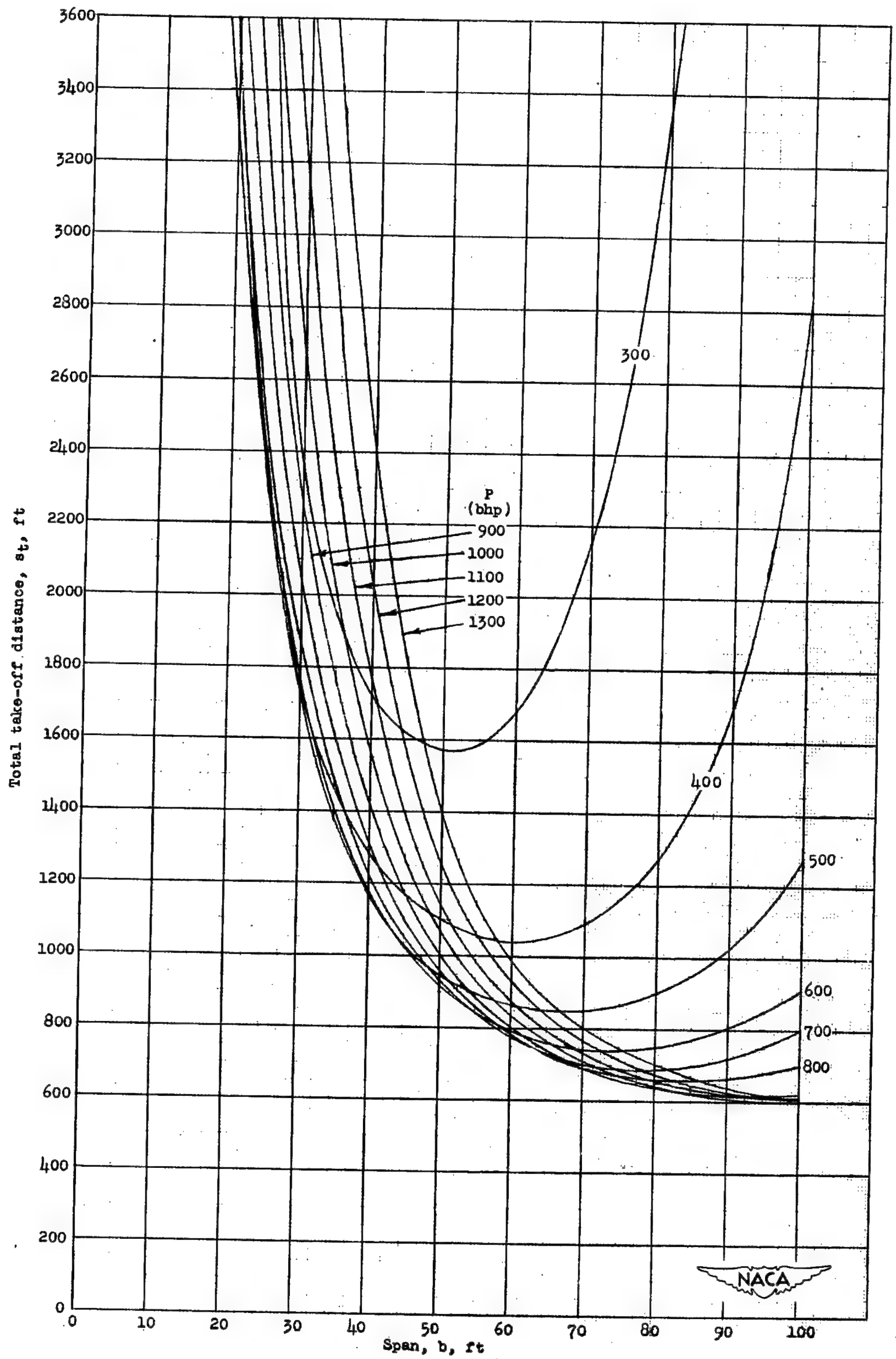
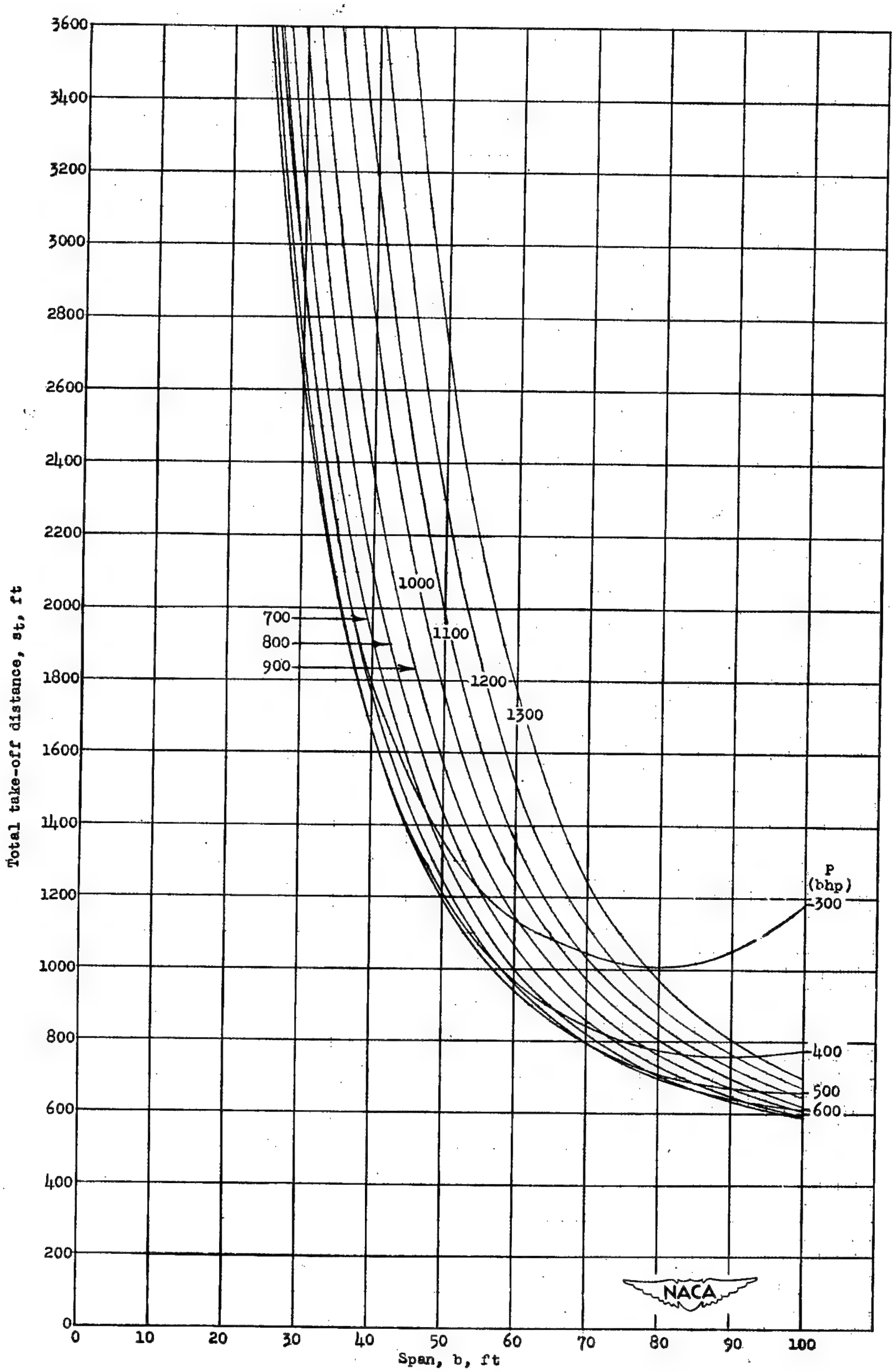


Figure 8.- Optimum maximum lift coefficient for minimum total take-off distance of an airplane with boundary-layer control as a function of wing loading for various aspect ratios and horsepowers.

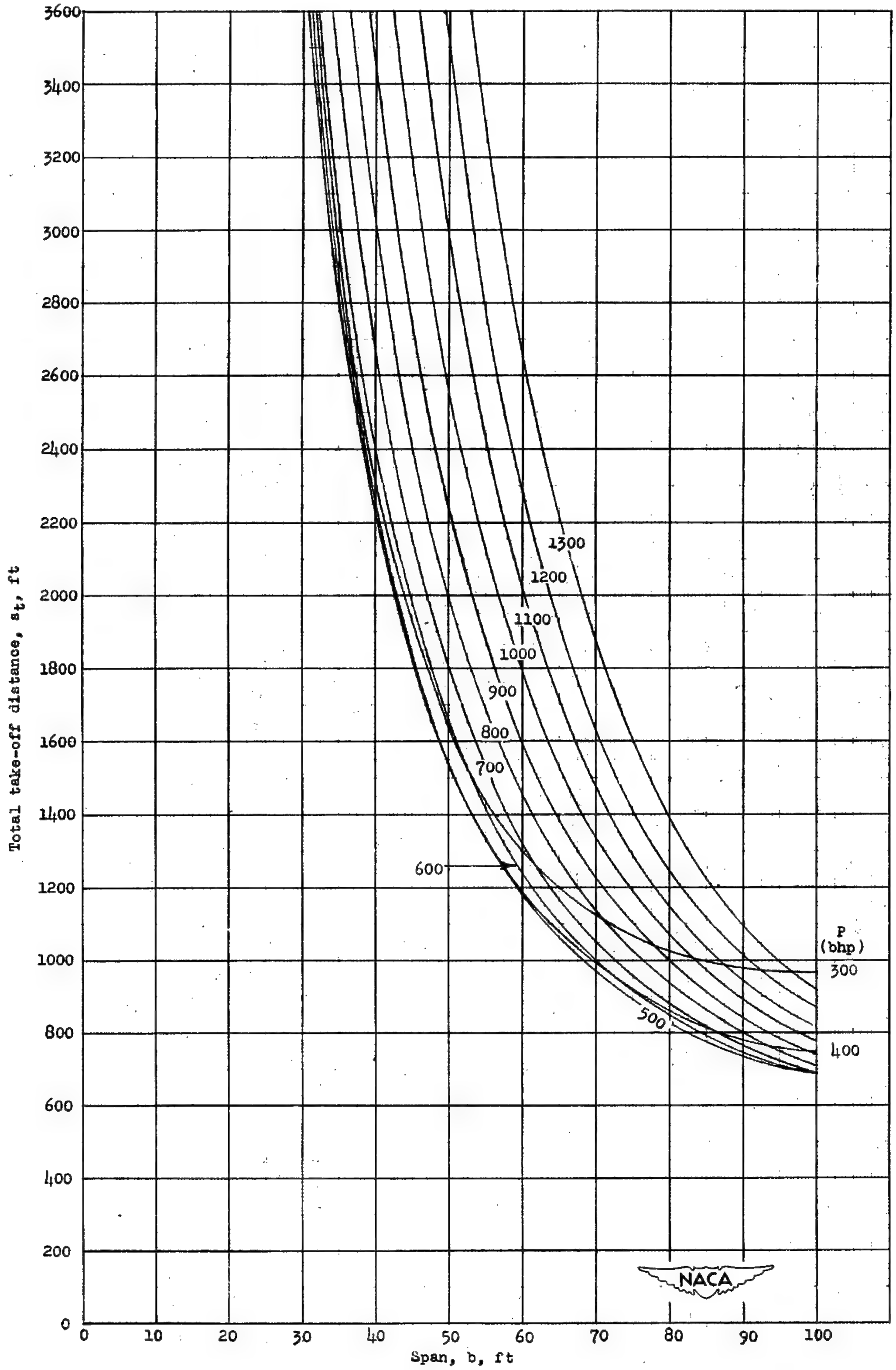


(a) A = 5.

Figure 9.- Total take-off distance of an airplane without boundary-layer control as a function of span for various powers.

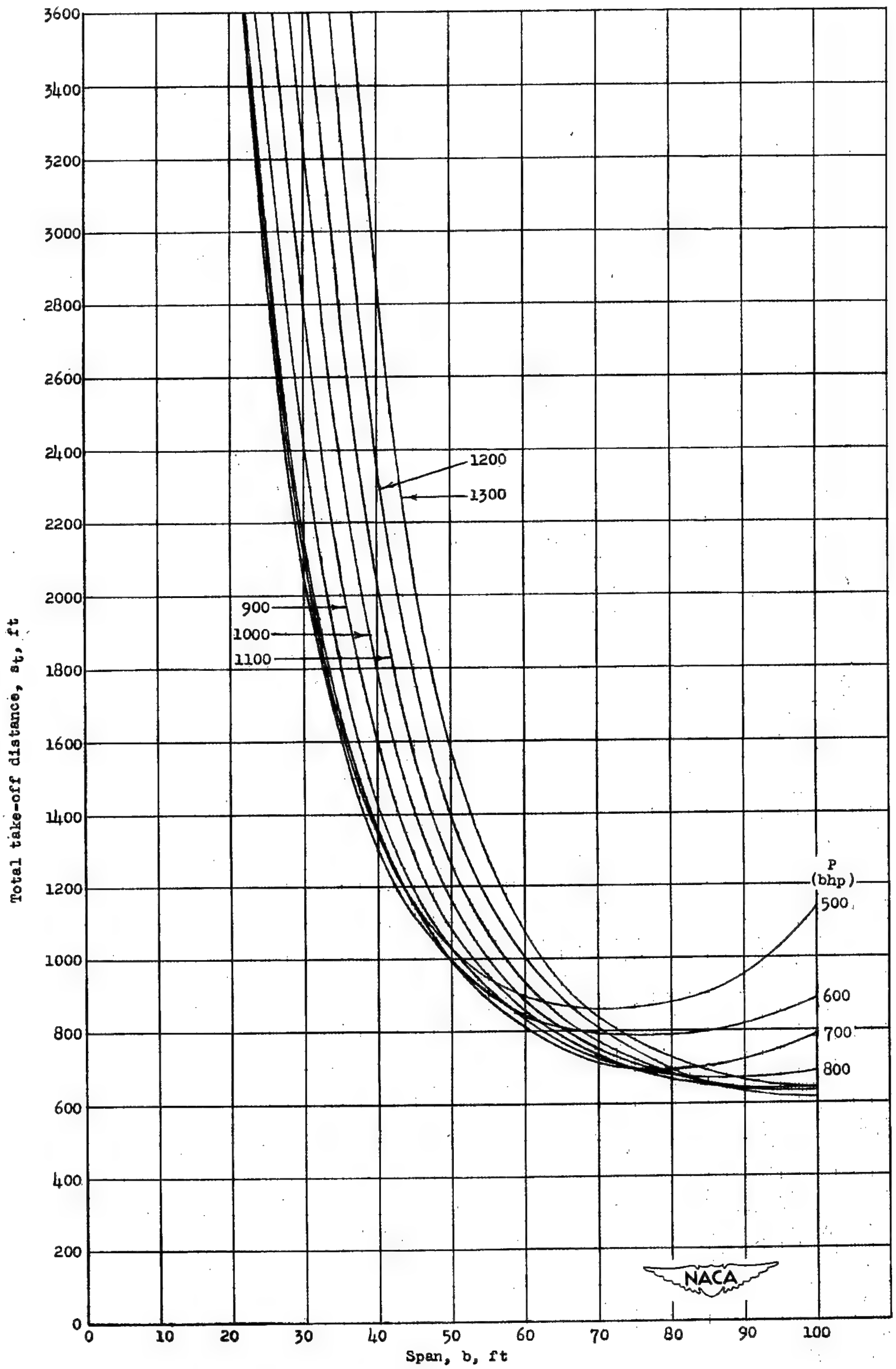


(b) A = 10.
Figure 9.- Continued.



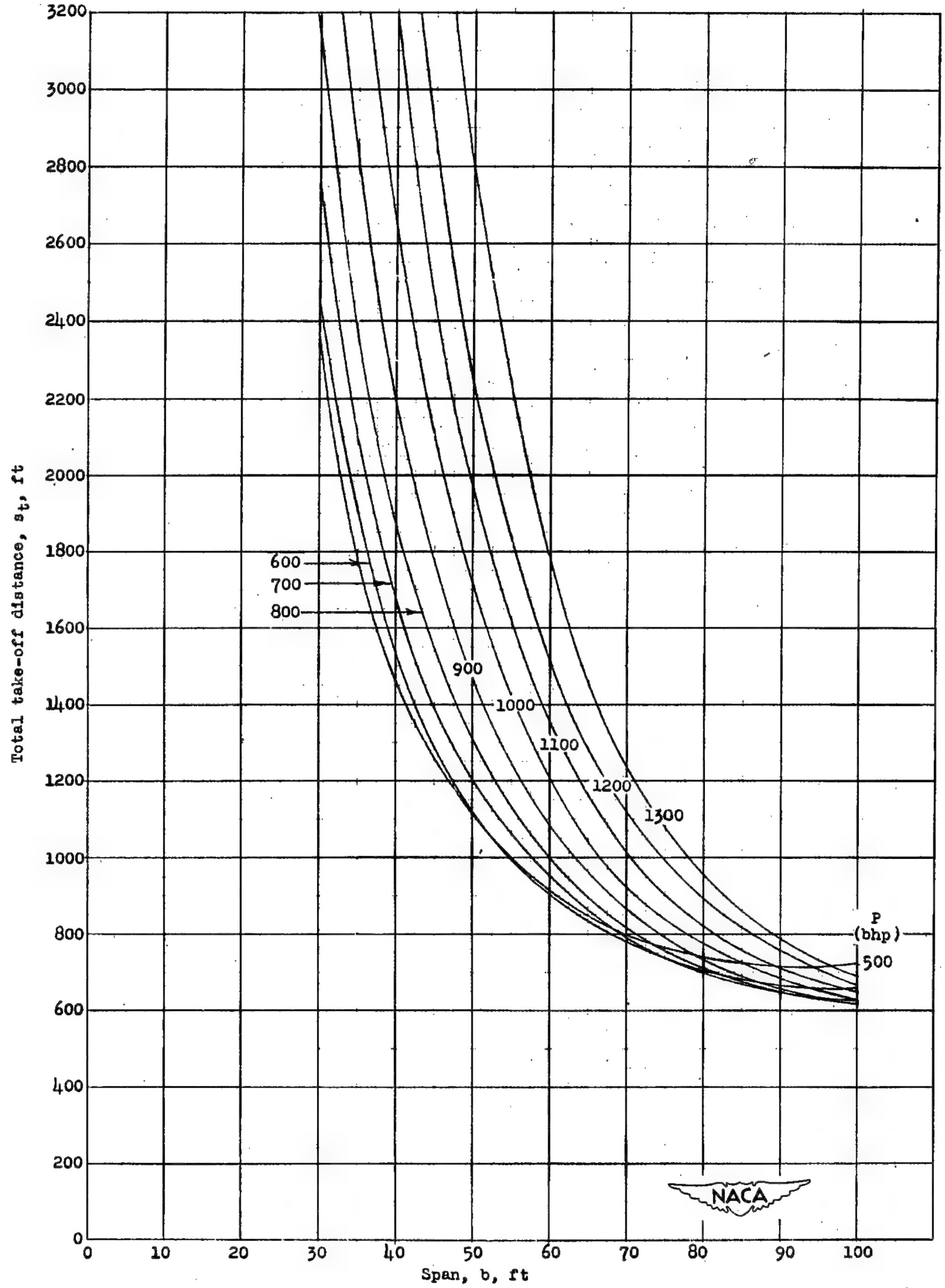
(c) A = 15.

Figure 9 .- Concluded.



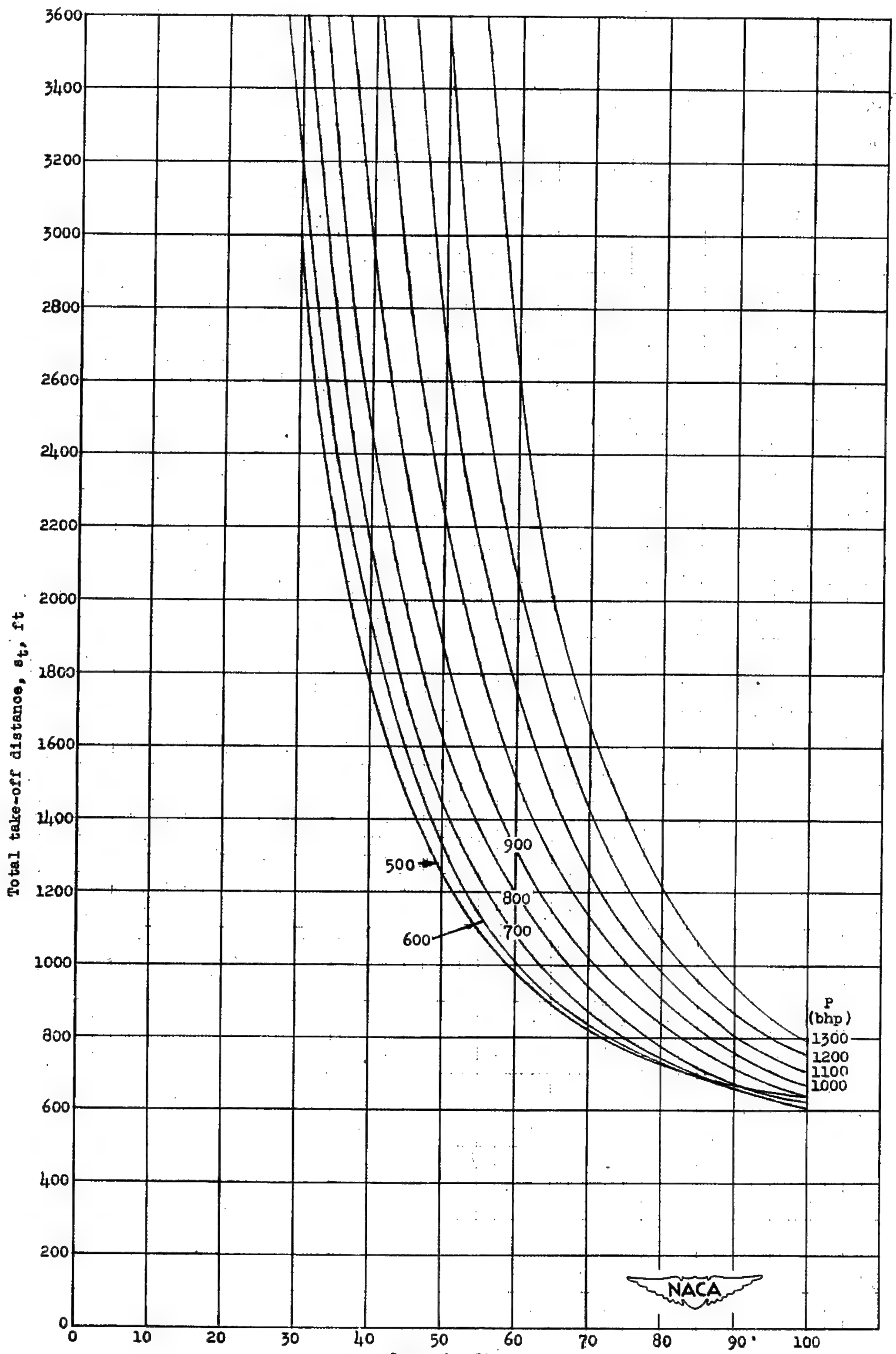
(a) A = 5.

Figure 10.- Total take-off distance of an airplane with boundary-layer control as a function of span for various powers.



(b) A = 10.

Figure 10 .- Continued.



(c) A = 15.

Figure 10.- Concluded.

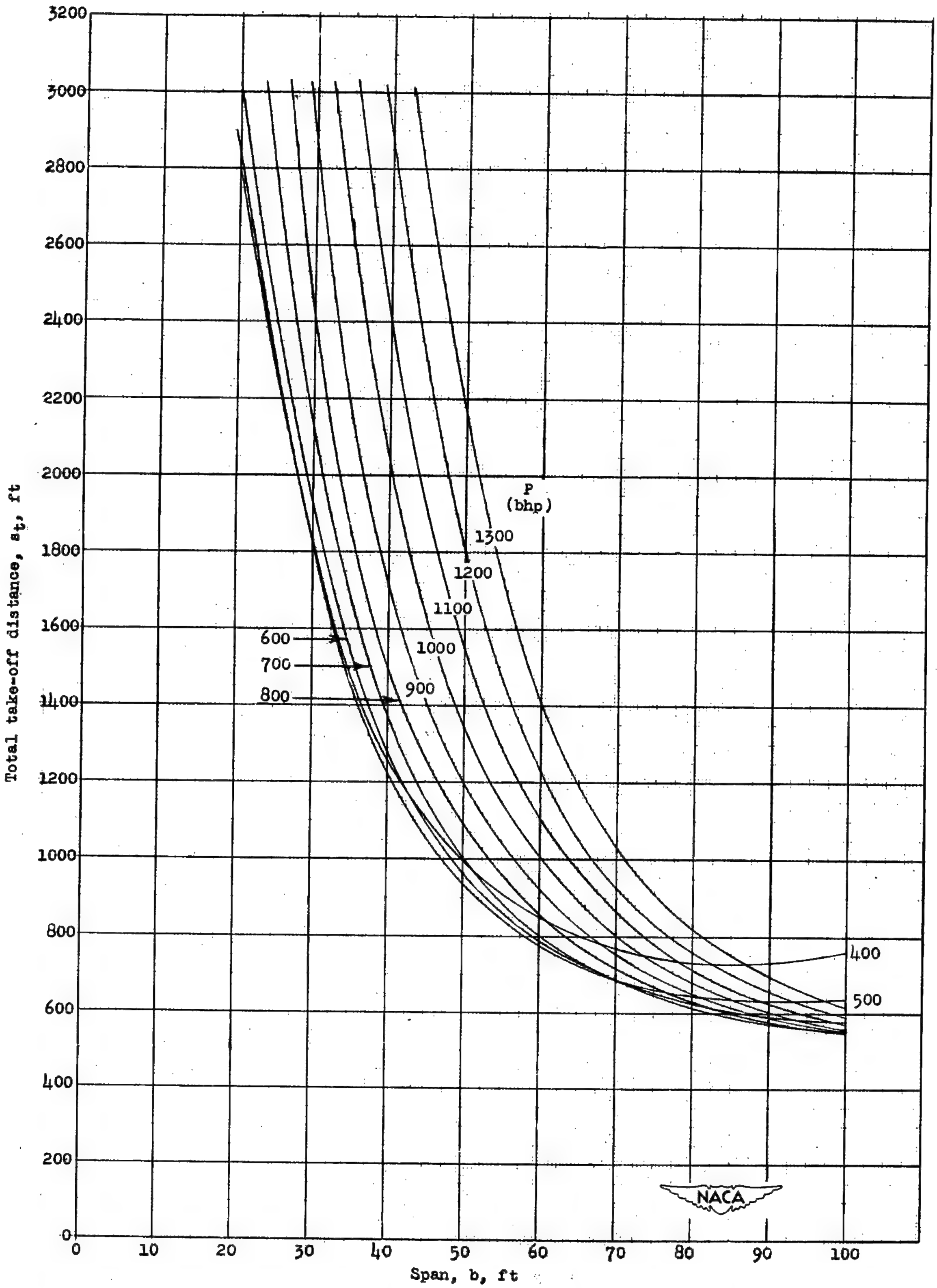
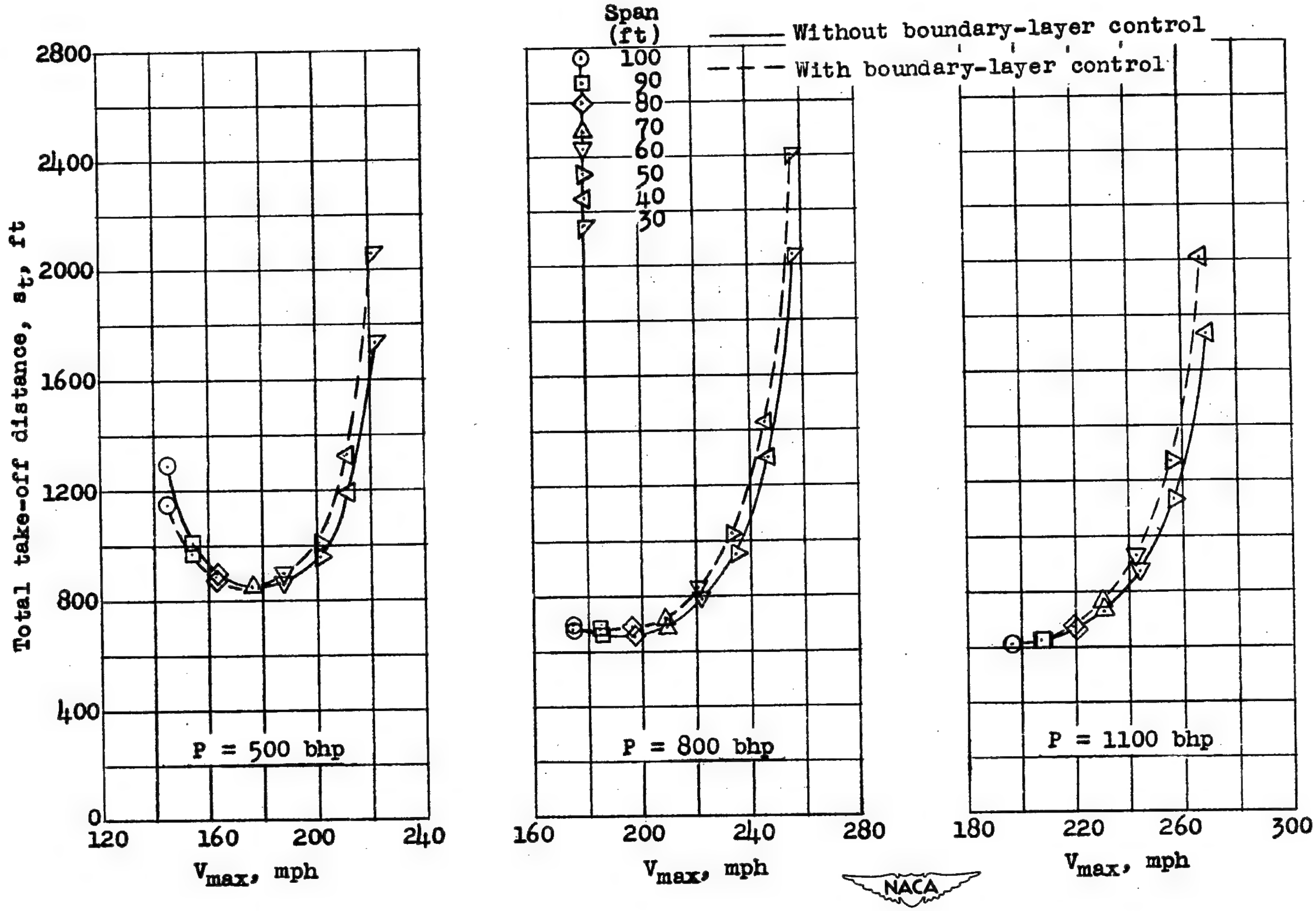
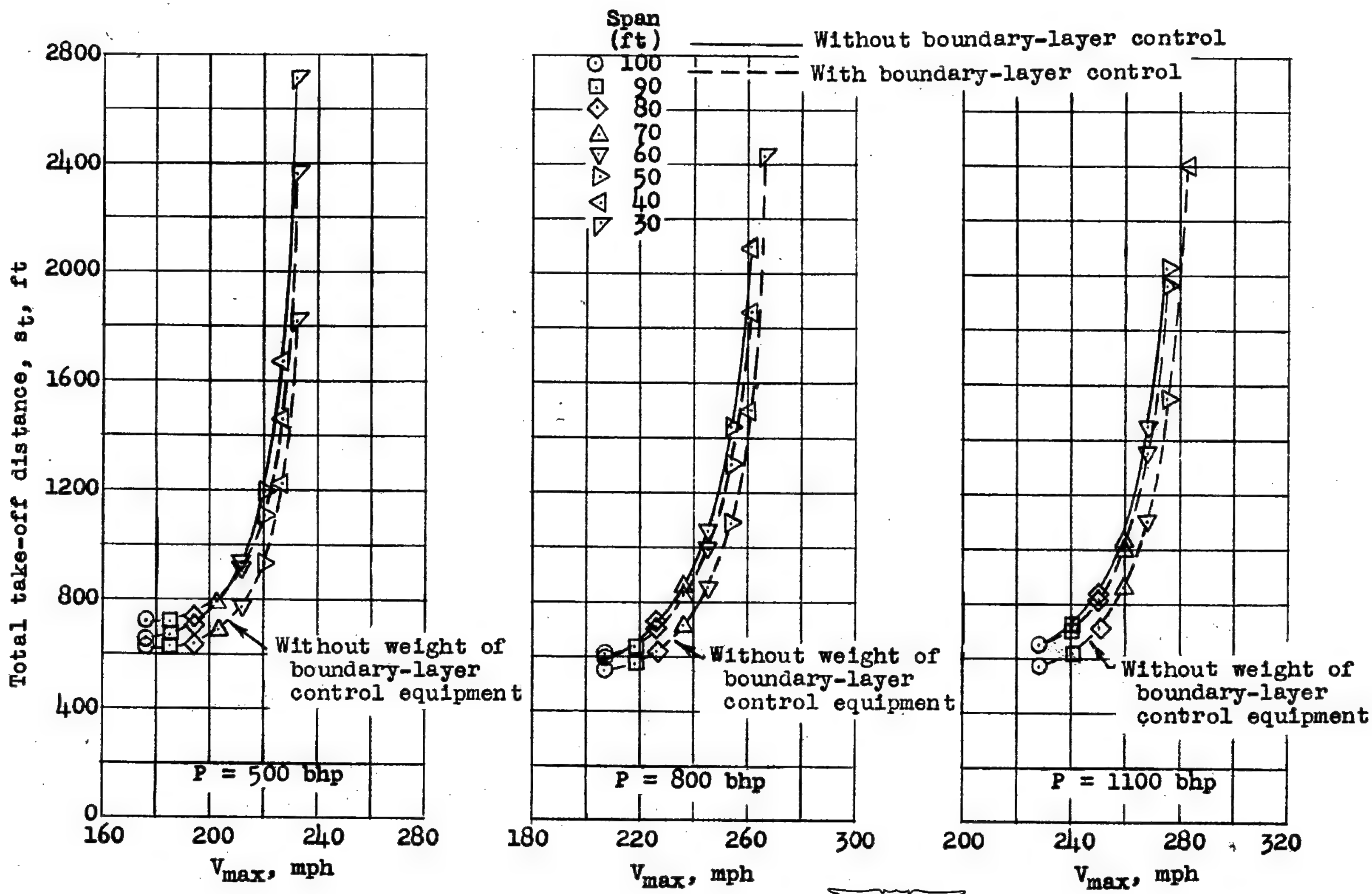


Figure 11.- Total take-off distance of an airplane with boundary-layer control, but with weight of boundary-layer control equipment excluded, as a function of span for various powers. A = 10.



(a) A = 5.

Figure 12.- Total take-off distance of an airplane with and without boundary-layer control as a function of maximum speed for various powers.



(b) A = 10.

Figure 12.- Continued.

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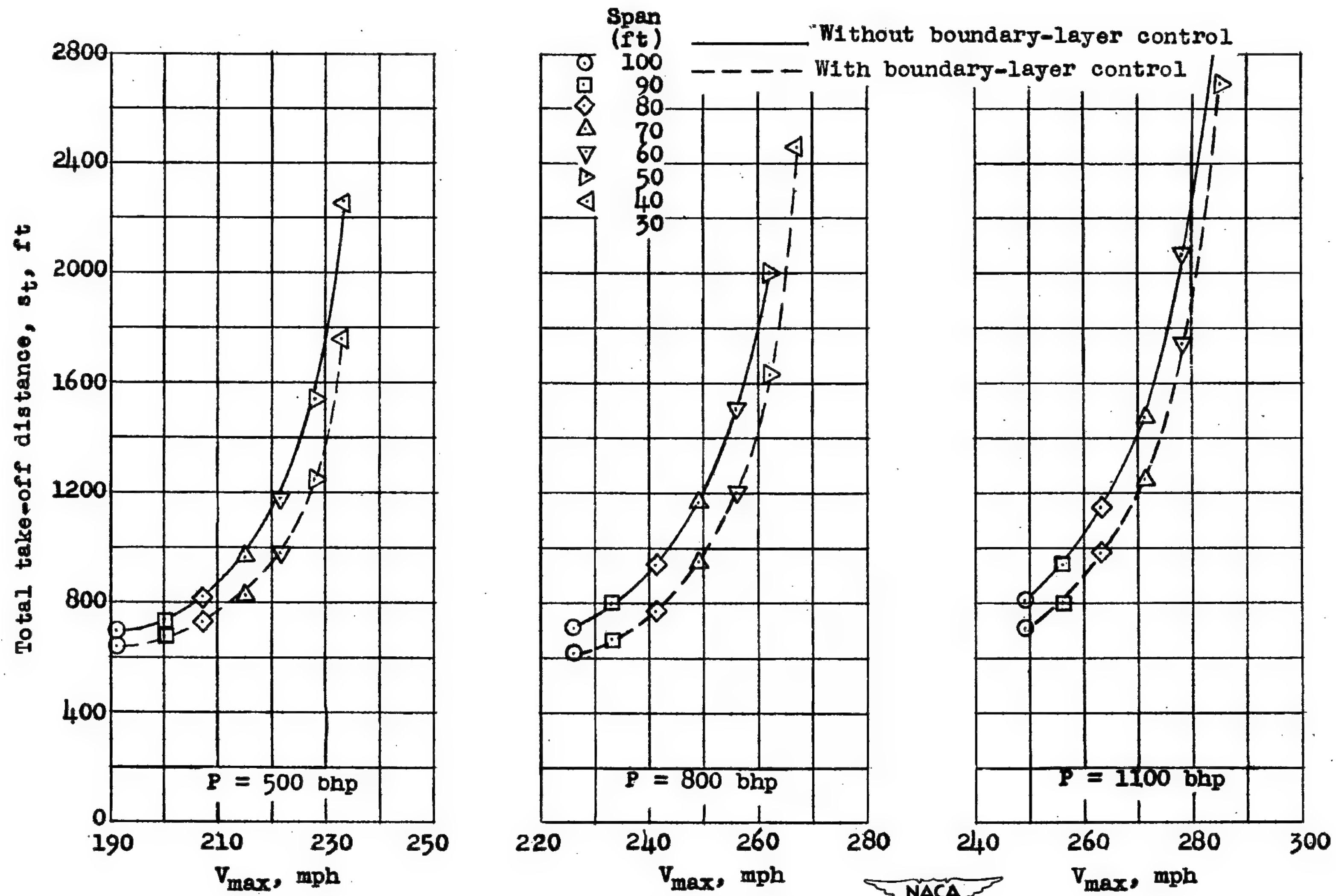
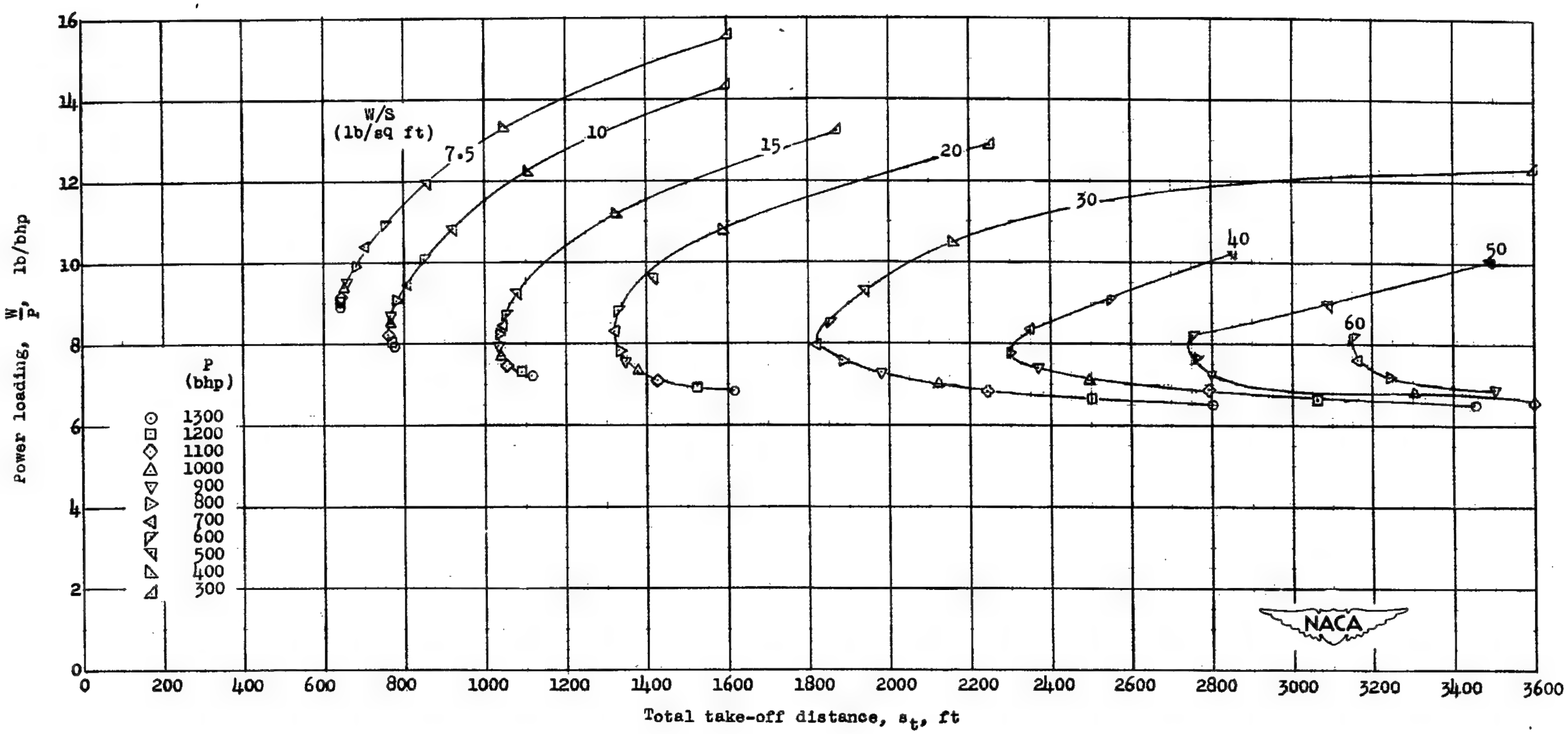


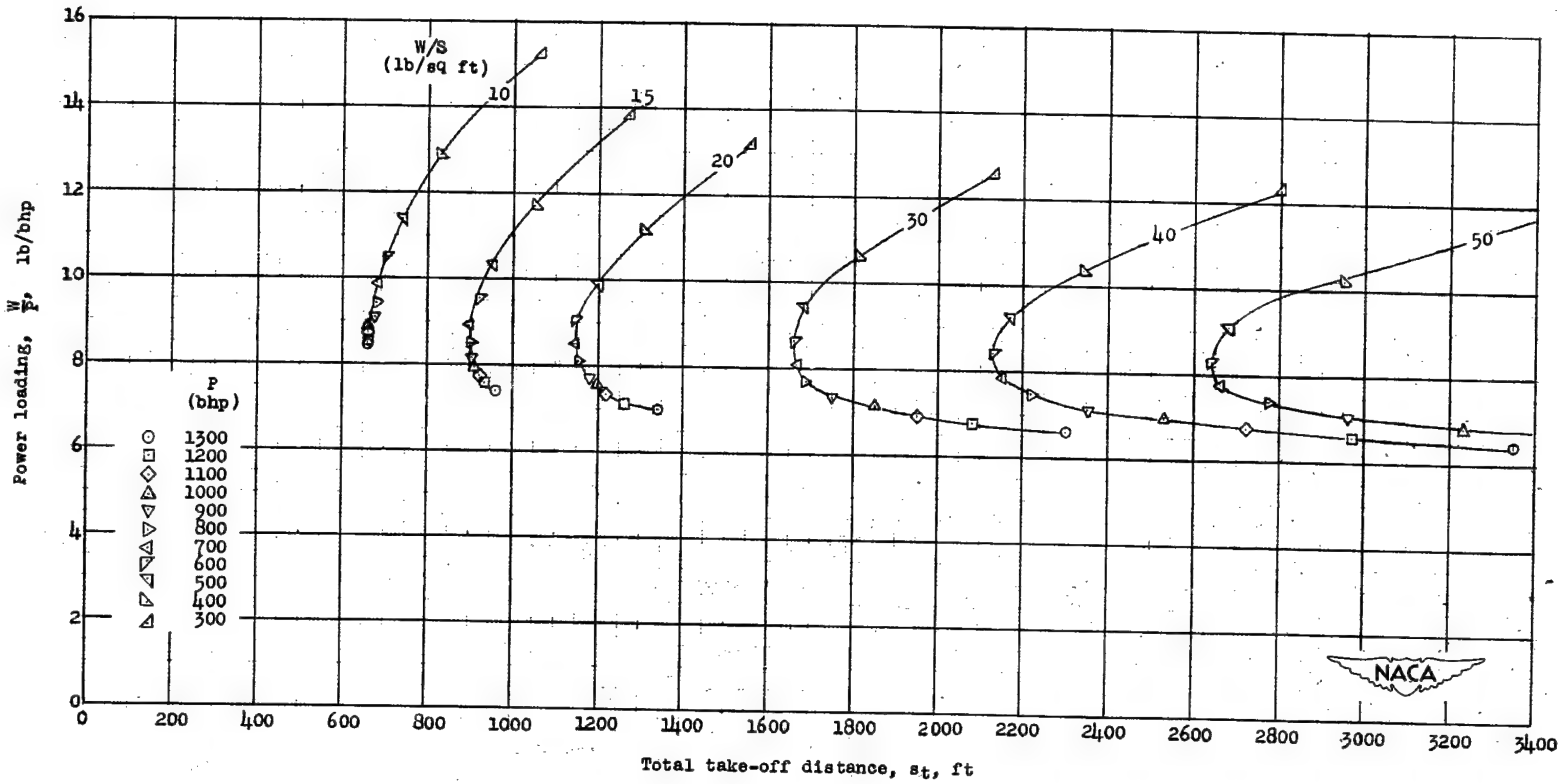
(c) A = 15.

Figure 12.- Concluded.



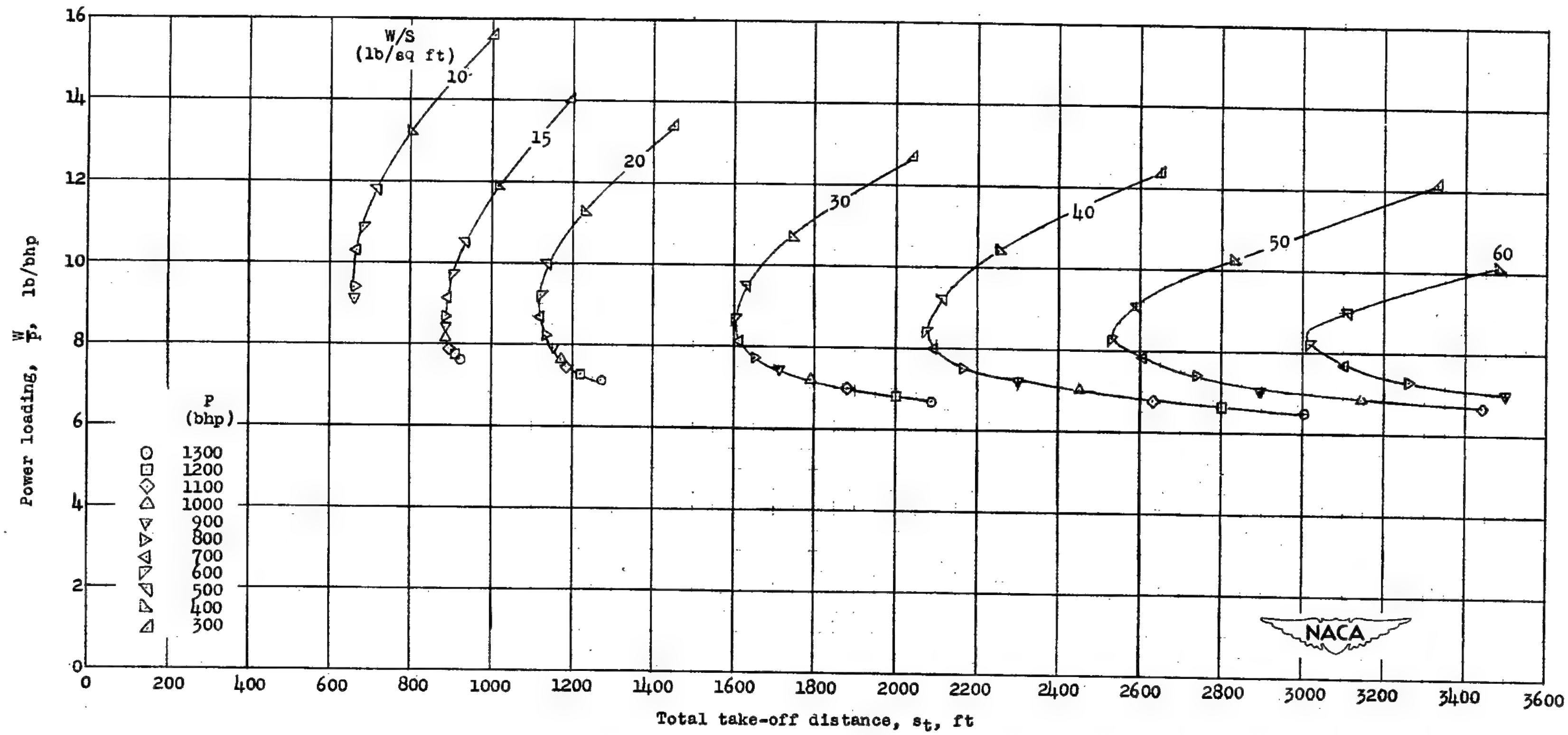
(a) A = 5.

Figure 13.- Total take-off distance of an airplane without boundary-layer control as a function of power loading for various wing loadings.



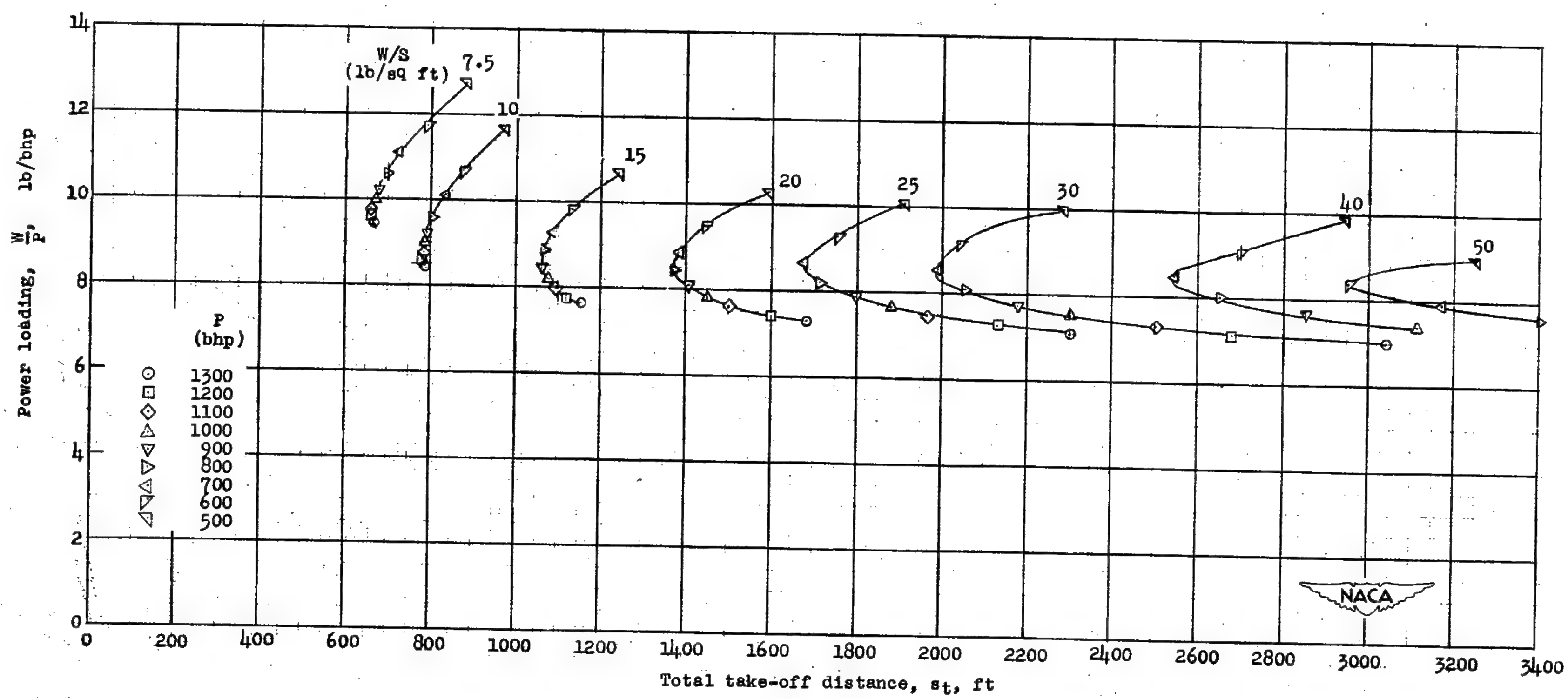
(b) A = 10.

Figure 13.- Continued.



(c) A = 15.

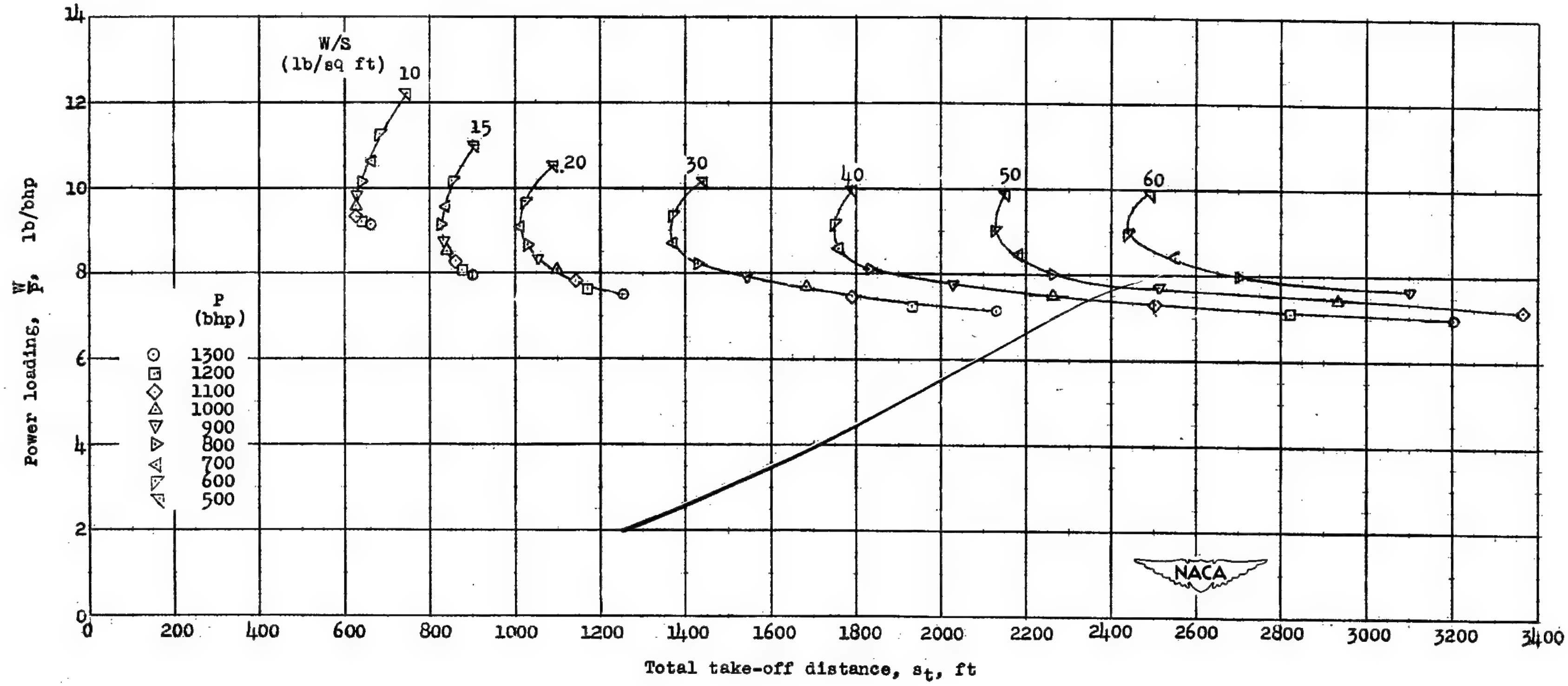
Figure 13.- Concluded.



(a) A = 5.

Figure 14.- Total take-off distance of an airplane with boundary-layer control as a function of power loading for various wing loadings.

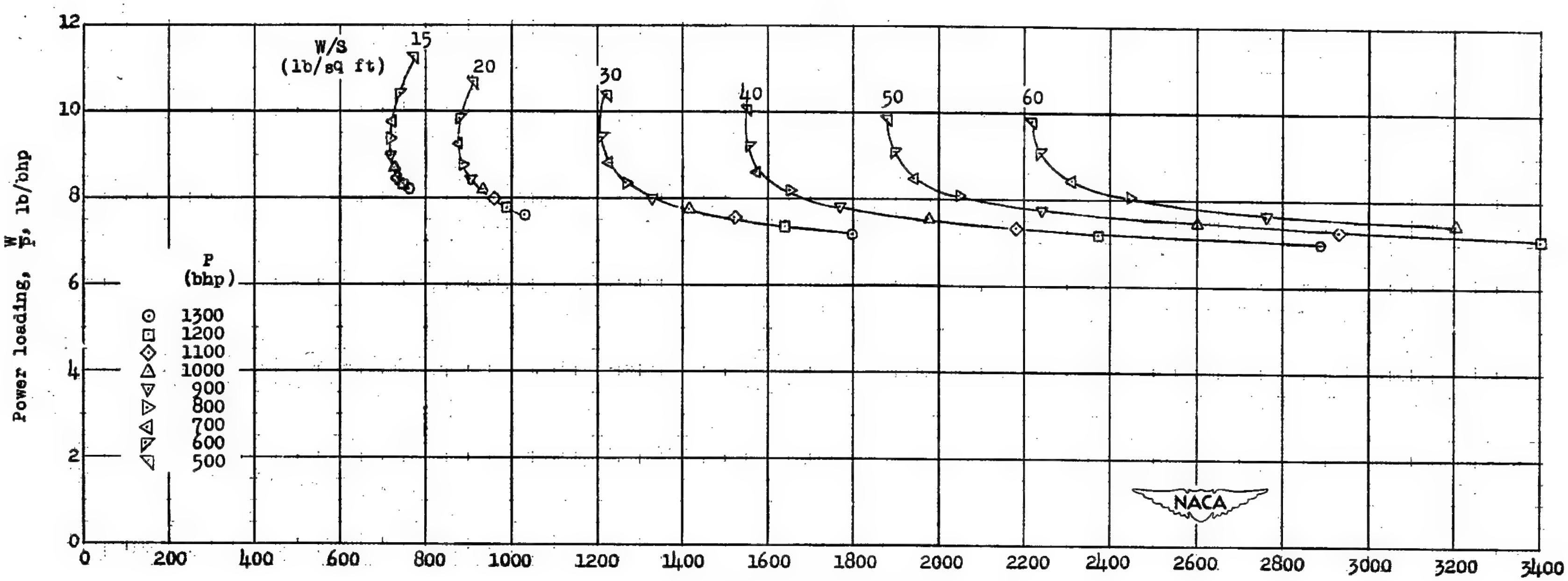
2333 14



(b) A = 10.

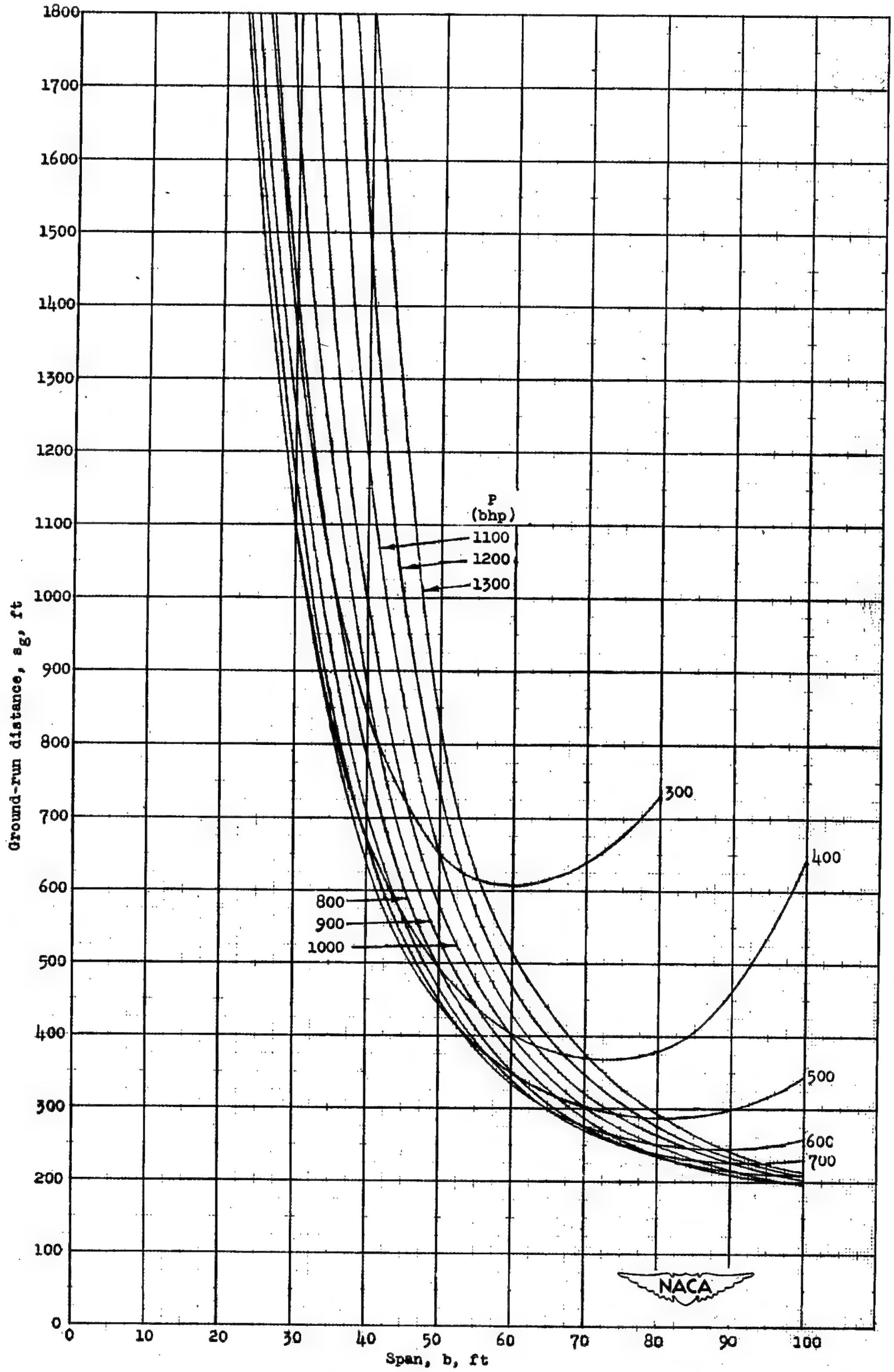
Figure 14.- Continued.

233314



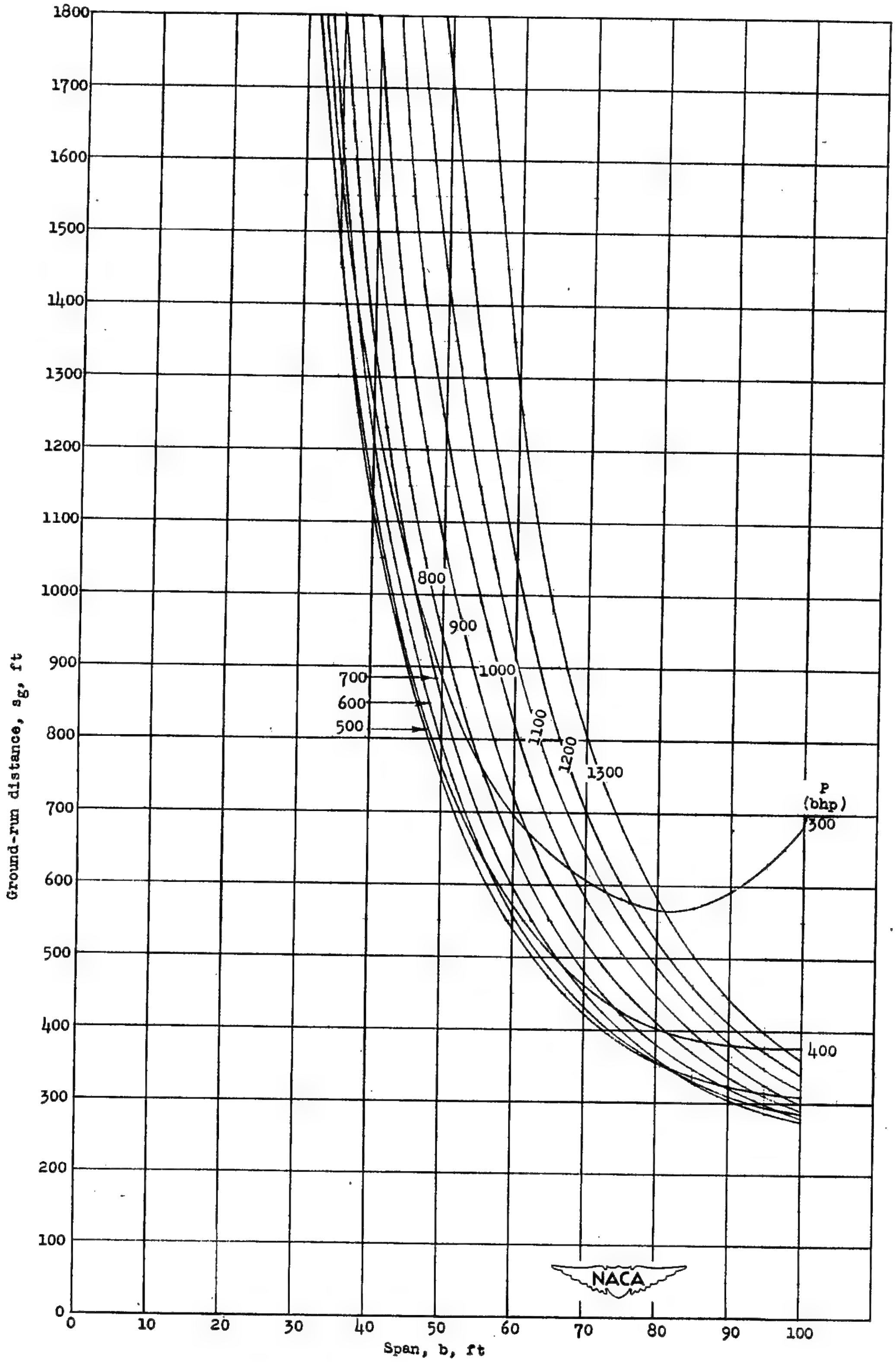
(c) A = 15.

Figure 14.- Concluded.

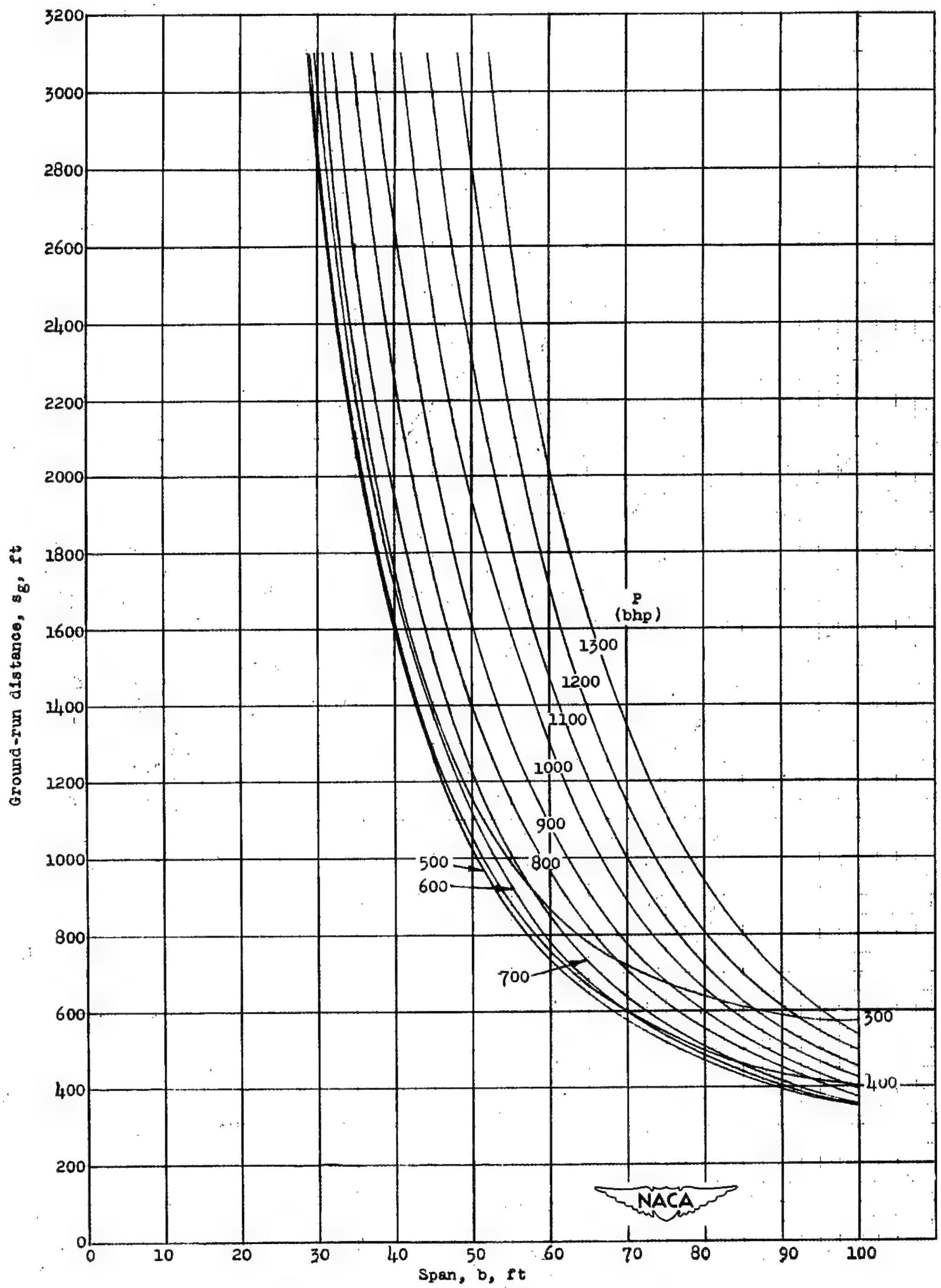


(a) A = 5.

Figure 15.- Ground-run distance of an airplane without boundary-layer control as a function of span for various powers.

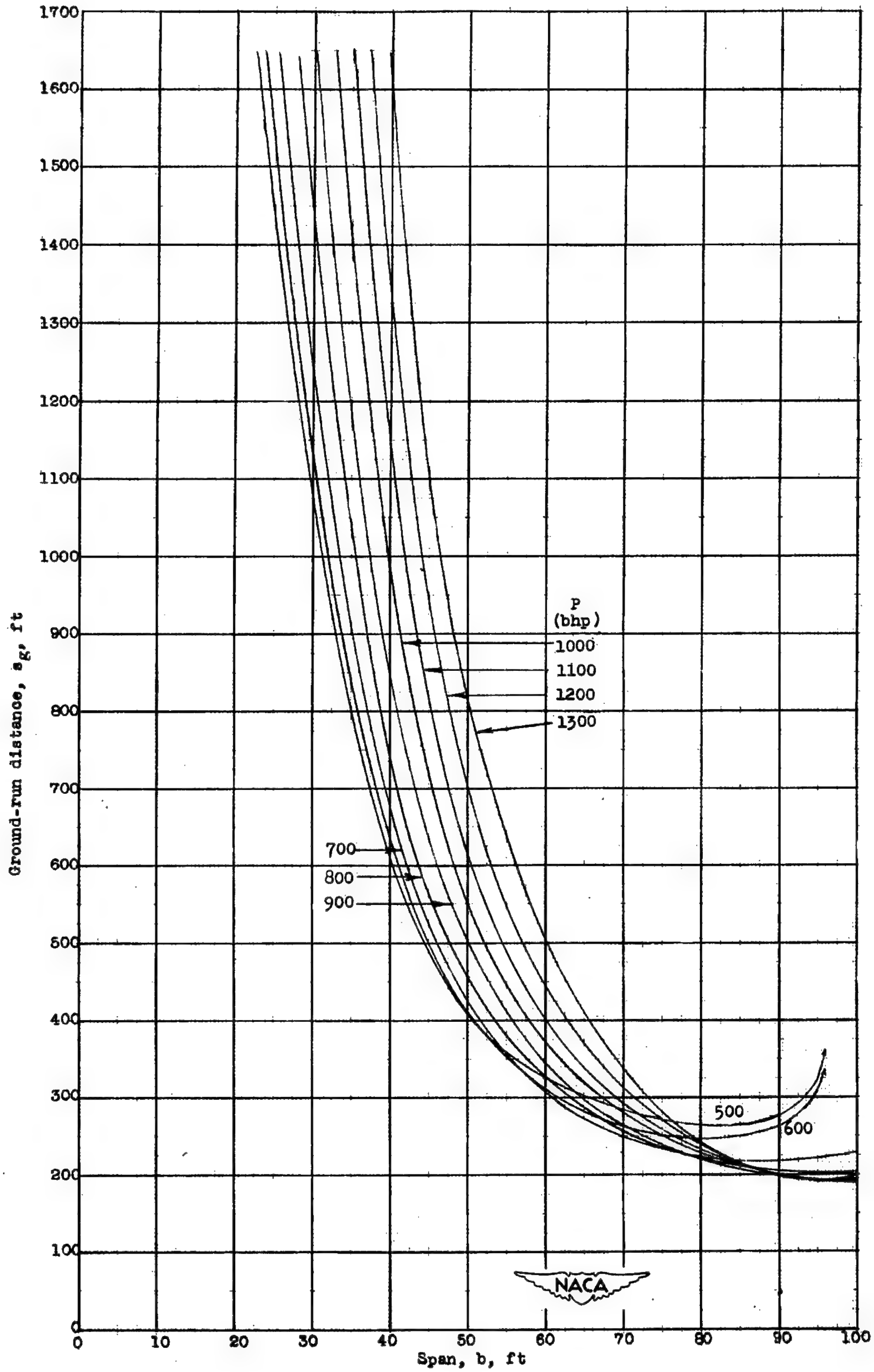


(b) A = 10.
Figure 15.- Continued.



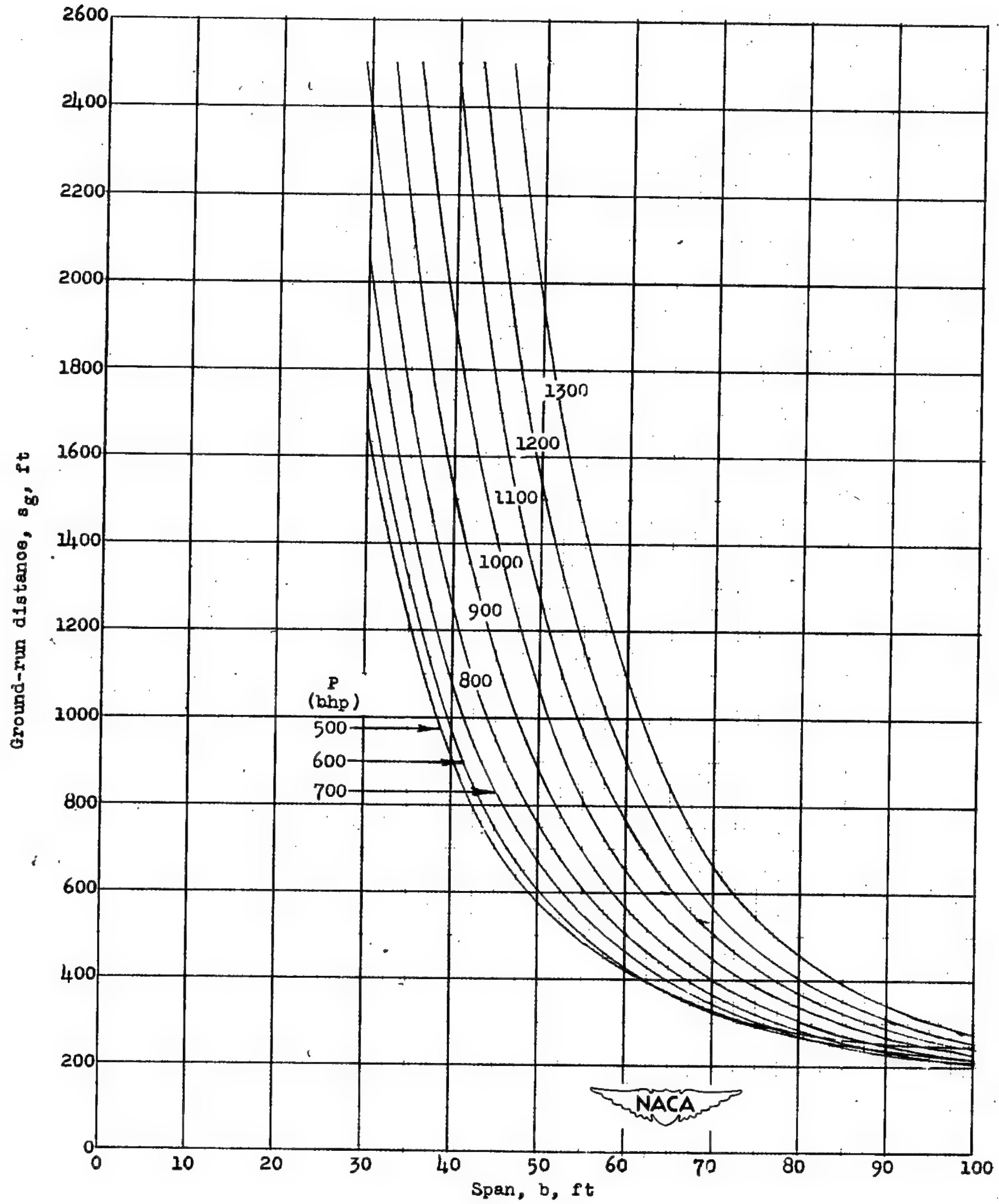
(c) A = 15.

Figure 15.- Concluded.



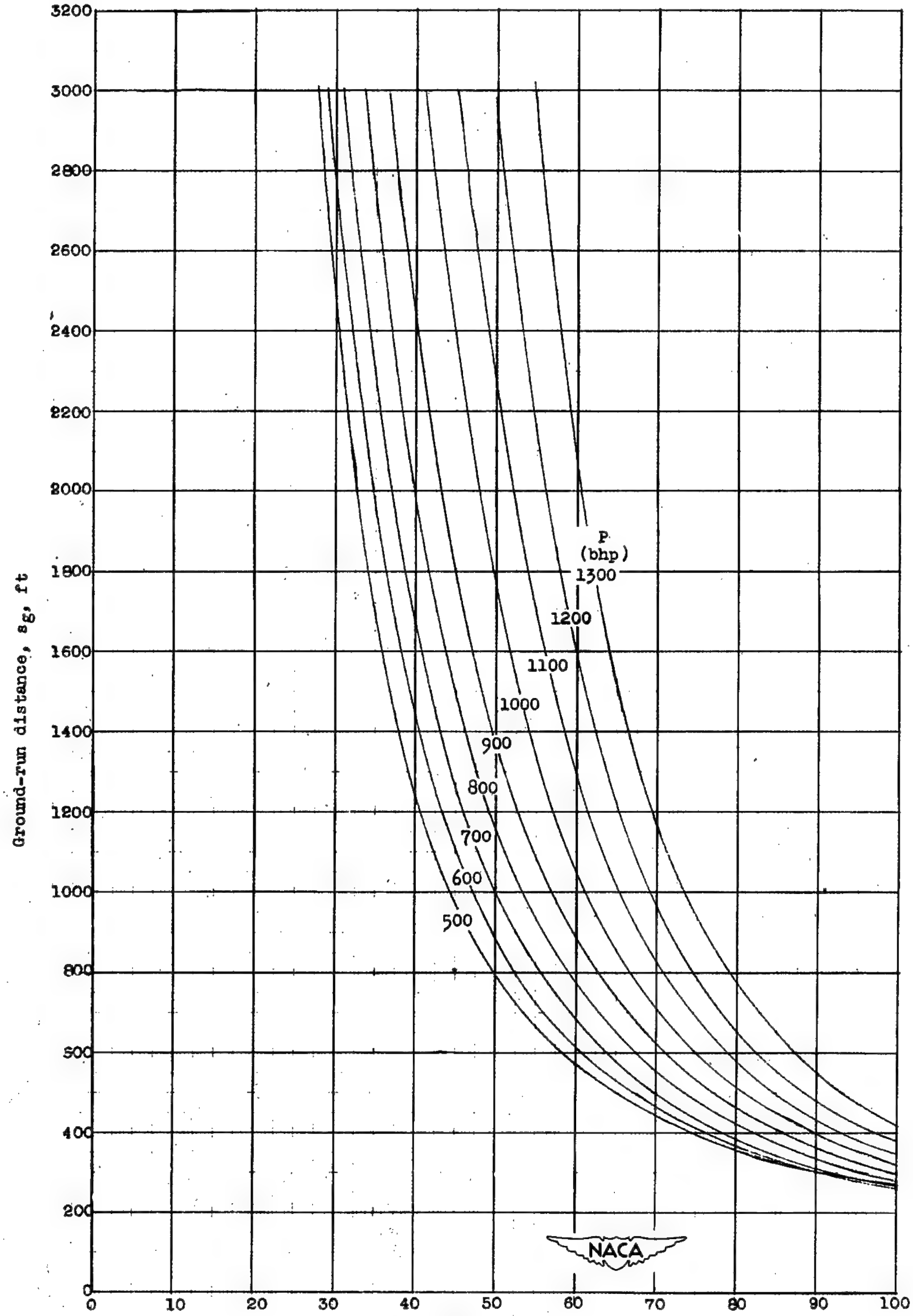
(a) A = 5.

Figure 16.- Ground-run distance of an airplane with boundary-layer control as a function of span for various powers.



(b) A = 10.

Figure 16.- Continued.



(c) $A = 15$.

Figure 16 .- Concluded.

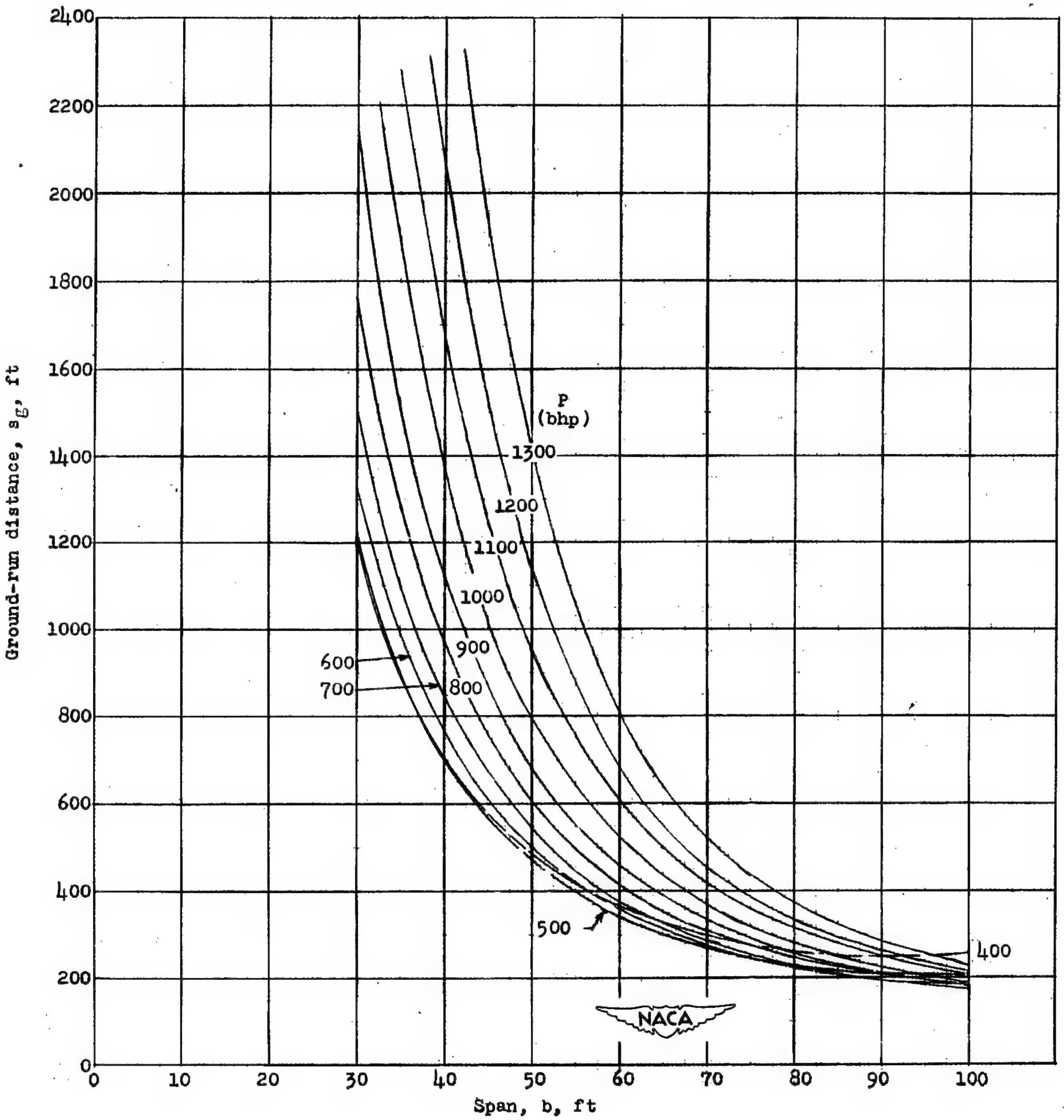


Figure 17.- Ground-run distance of an airplane with boundary-layer control, but with weight of boundary-layer equipment excluded, as a function of span for various powers. A = 10.

233318

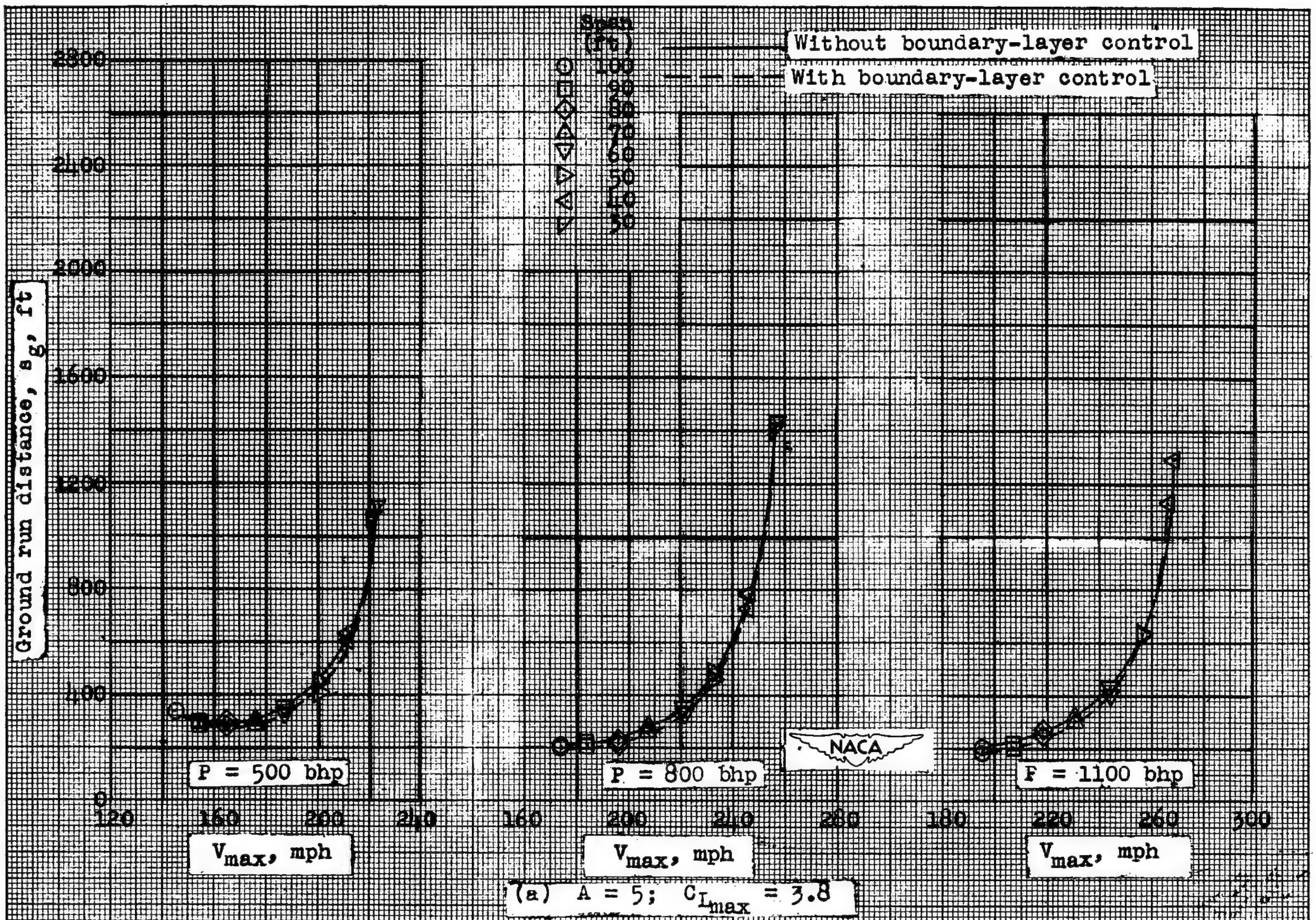
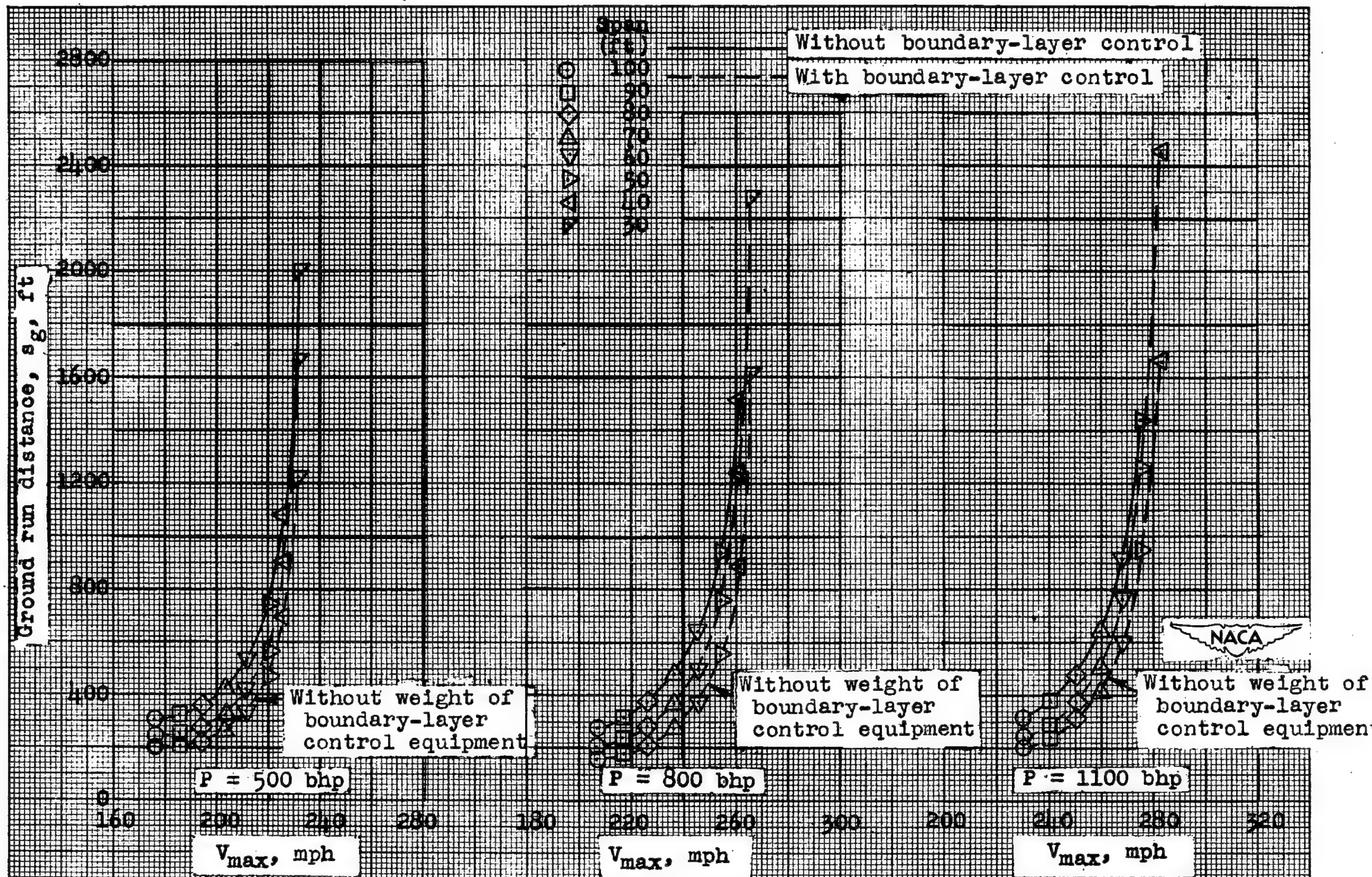


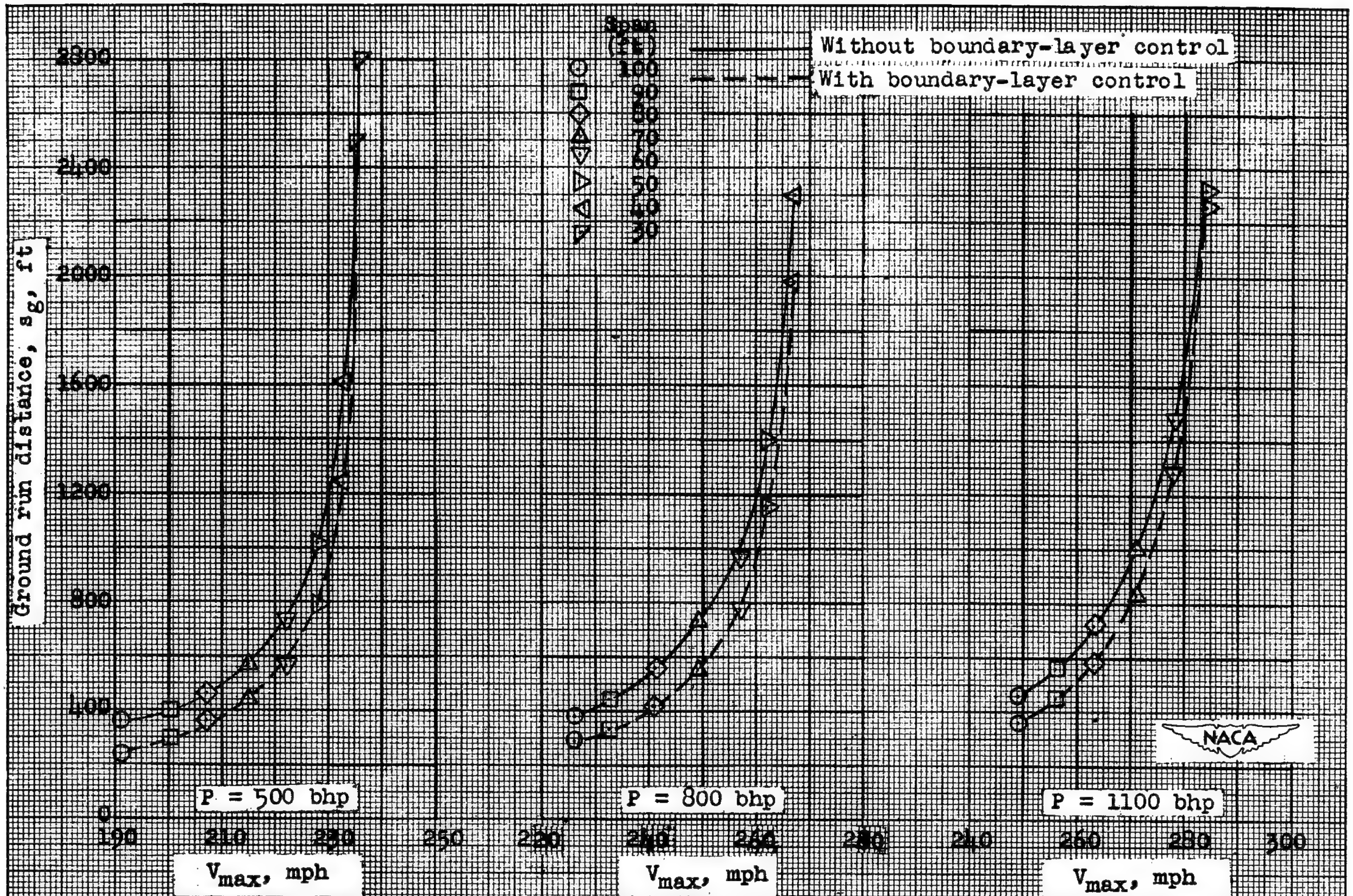
Figure 18.- Ground run distance of an airplane with and without boundary-layer control as a function of maximum speed for various powers.



(b) $A = 10$; $C_{L_{max}} = 5.0$.

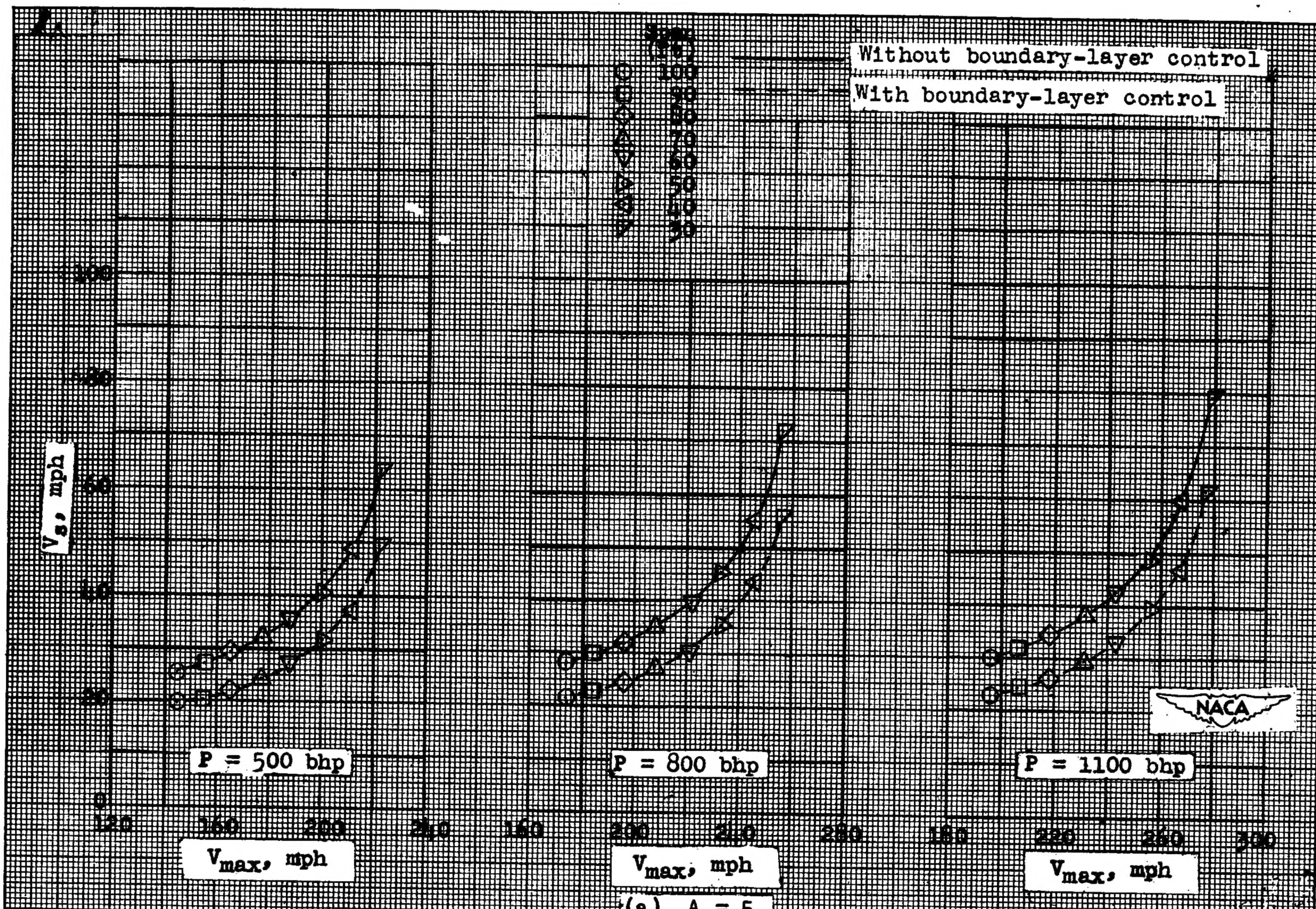
Figure 18.- Continued.

233318



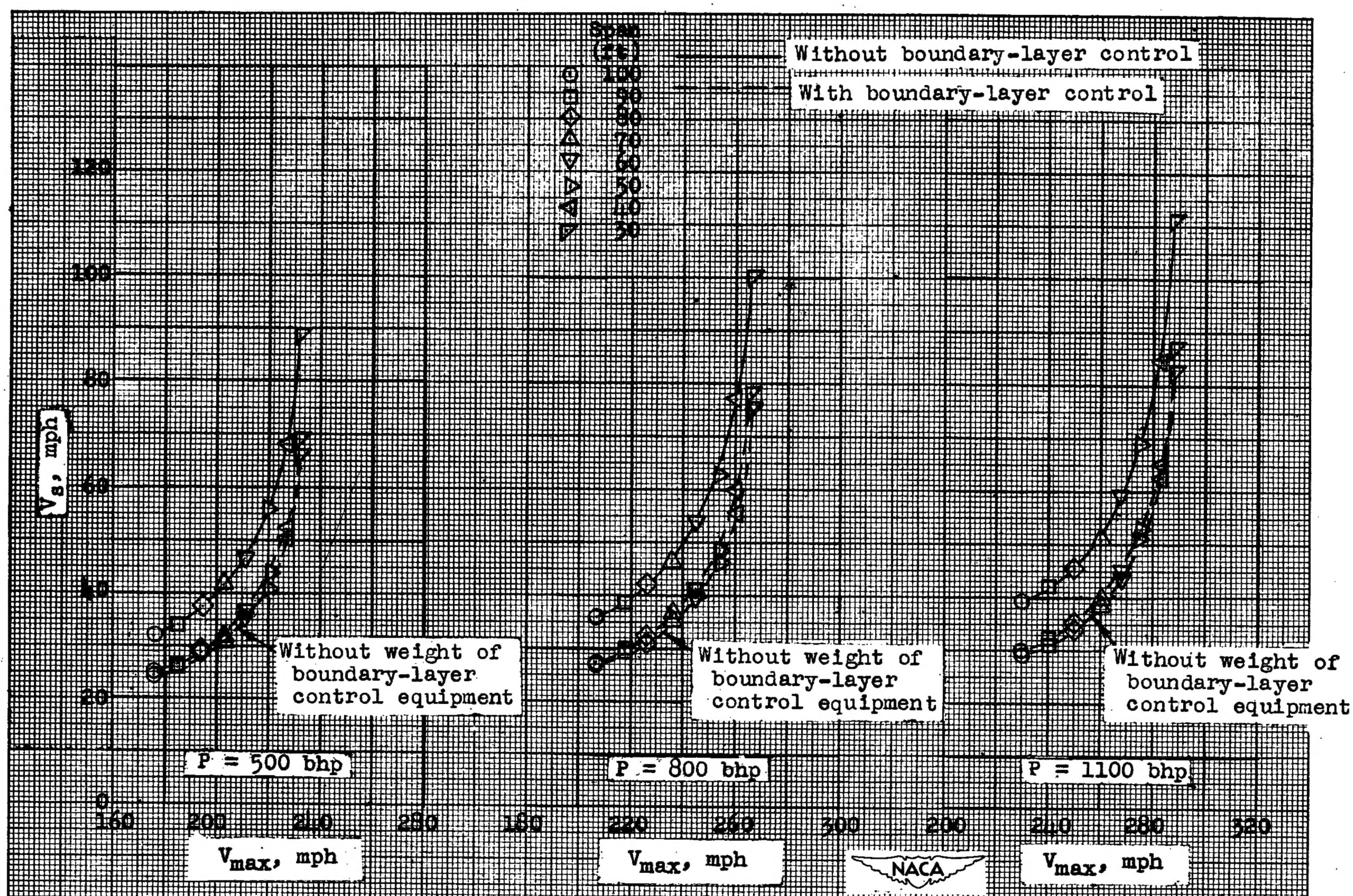
(c) $A = 15$; $C_{L_{max}} = 5.0$.

Figure 18.- Concluded.



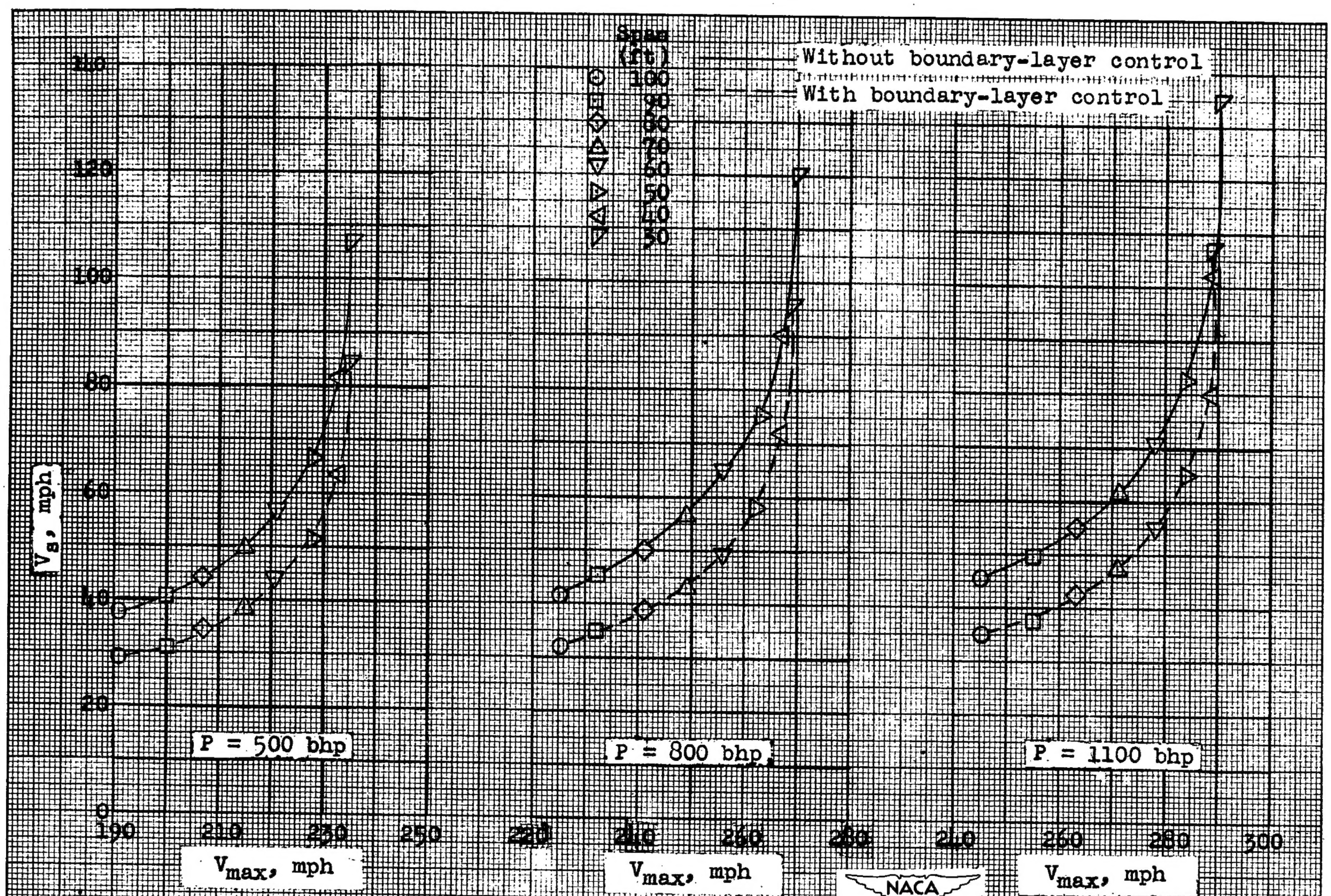
(a) A = 5.

Figure 19.- Stalling speed of an airplane with and without boundary-layer control as a function of maximum speed for various powers.



(b) A = 10.

Figure 19.- Continued.



(c) A = 15.

Figure 19.- Concluded.

ANALYSIS OF THE EFFECTS OF BOUNDARY-LAYER CONTROL

ON THE TAKE-OFF PERFORMANCE CHARACTERISTICS

OF A LIAISON-TYPE AIRPLANE

By Elmer A. Horton and John H. Quinn, Jr.

INDEX

ABSTRACT

A performance analysis is given to determine whether boundary-layer control by suction might reduce the minimum take-off distance of a four- or five-place airplane. Results indicate that boundary-layer control might be effective in improving the take-off characteristics of this type airplane having wing loadings of 10 or more pounds per square foot and aspect ratios of 10 or more.